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(54) **TRAILER MOTION AND PARAMETER ESTIMATION SYSTEM**

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(58) **Field of Classification Search**

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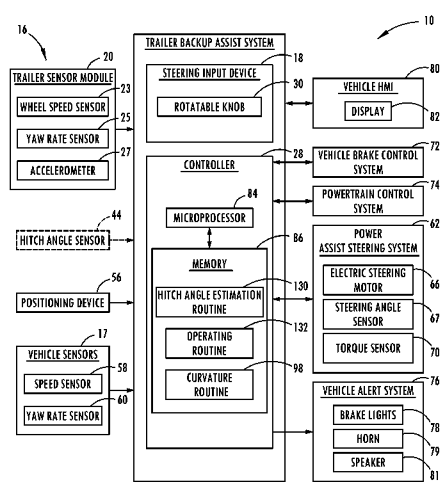
(57) **ABSTRACT**

A trailer backup assist system for a vehicle reversing a trailer includes a sensor module adapted to attach to the trailer and generate a trailer yaw rate or a trailer speed. The trailer backup assist system also includes a vehicle sensor system that generates a vehicle yaw rate and a vehicle speed. Further, the trailer backup assist system includes a controller that estimates a hitch angle based on the trailer yaw rate or the trailer speed and the vehicle yaw rate and the vehicle speed in view of a kinematic relationship between the trailer and the vehicle.

18 Claims, 9 Drawing Sheets



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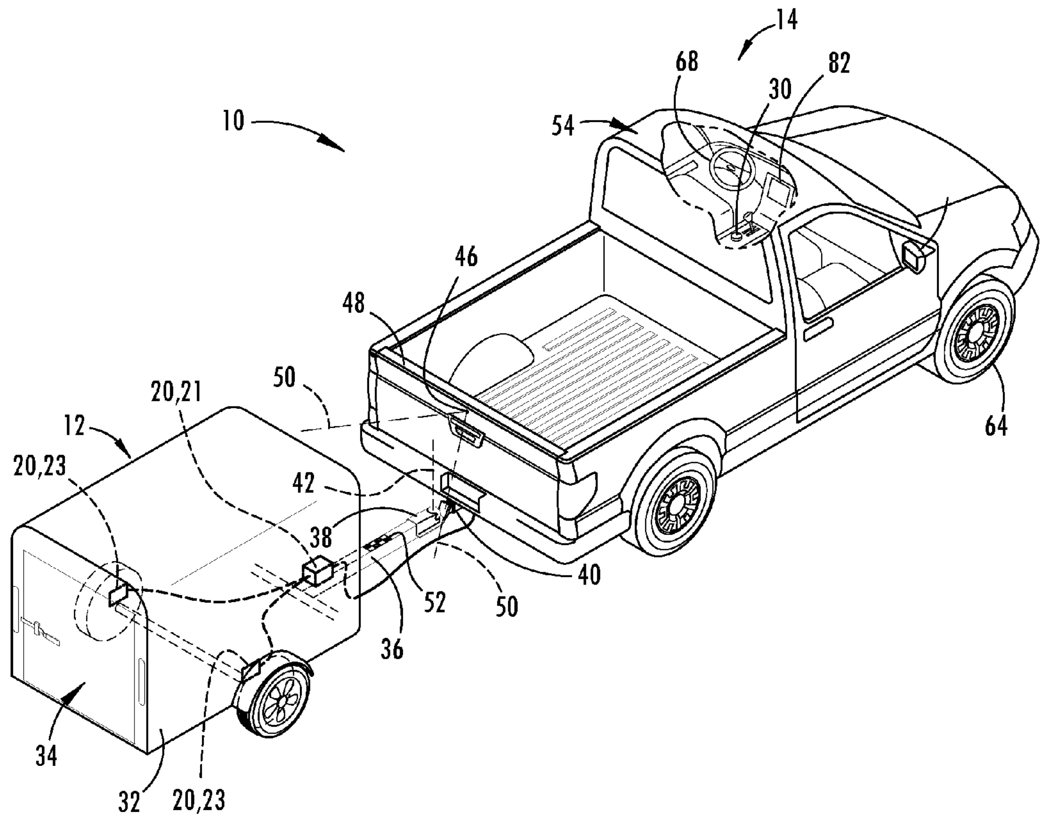
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68
82
30
10
54
46
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20,21
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42
38
40
52
50
36
64
34
32
20,23

FIG. 1

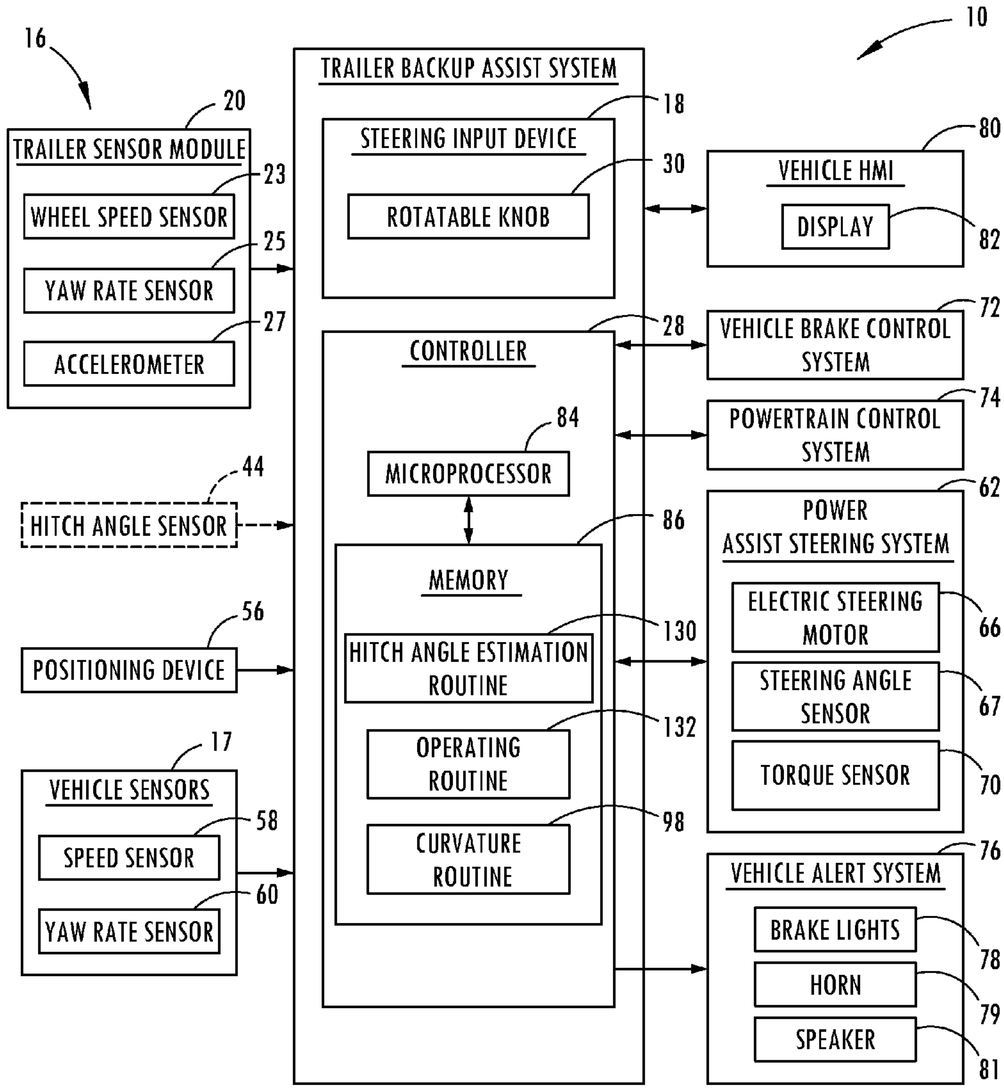

10
16
TRAILER BACKUP ASSIST SYSTEM
18
STEERING INPUT DEVICE
30
ROTATABLE KNOB
20
TRAILER SENSOR MODULE
23
WHEEL SPEED SENSOR
25
YAW RATE SENSOR
27
ACCELEROMETER
80
VEHICLE HMI
DISPLAY
82
28
CONTROLLER
VEHICLE BRAKE CONTROL SYSTEM
72
POWERTRAIN CONTROL SYSTEM
74
84
MICROPROCESSOR
44
HITCH ANGLE SENSOR
86
MEMORY
62
POWER ASSIST STEERING SYSTEM
ELECTRIC STEERING MOTOR
66
STEERING ANGLE SENSOR
67
TORQUE SENSOR
70
56
POSITIONING DEVICE
130
HITCH ANGLE ESTIMATION ROUTINE
132
OPERATING ROUTINE
98
CURVATURE ROUTINE
17
VEHICLE SENSORS
58
SPEED SENSOR
60
YAW RATE SENSOR
76
VEHICLE ALERT SYSTEM
BRAKE LIGHTS
78
HORN
79
SPEAKER
81

FIG. 2

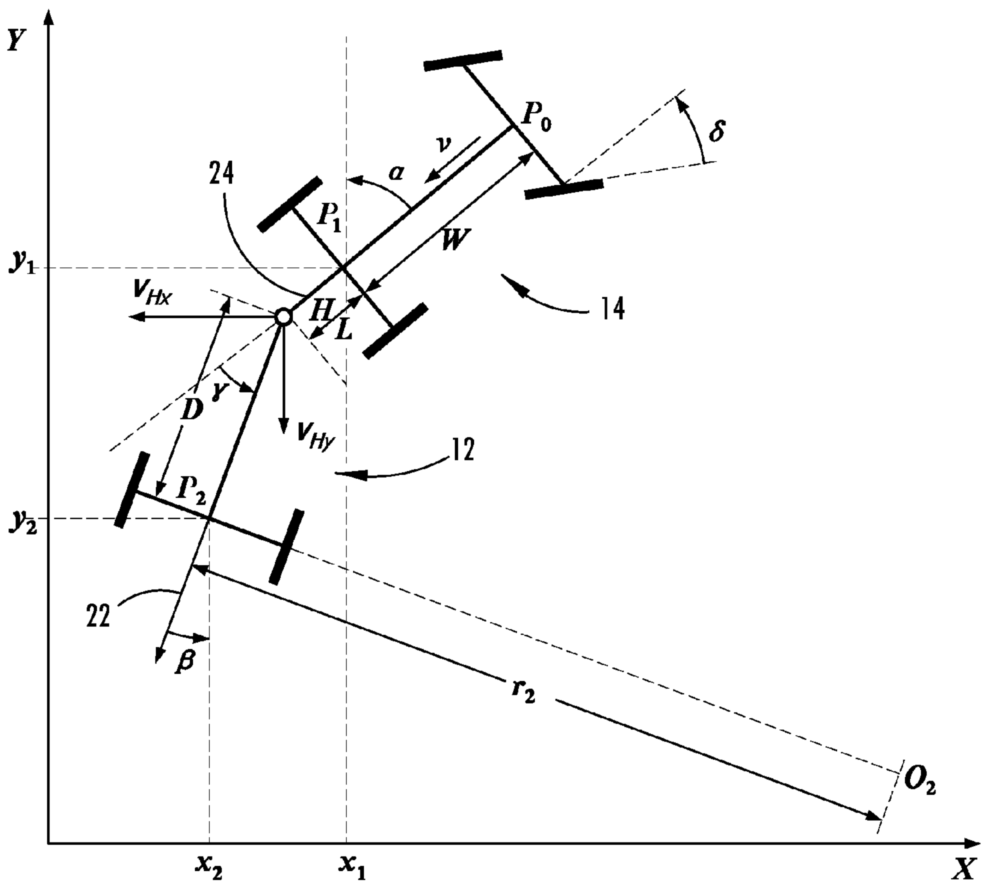


FIG. 3

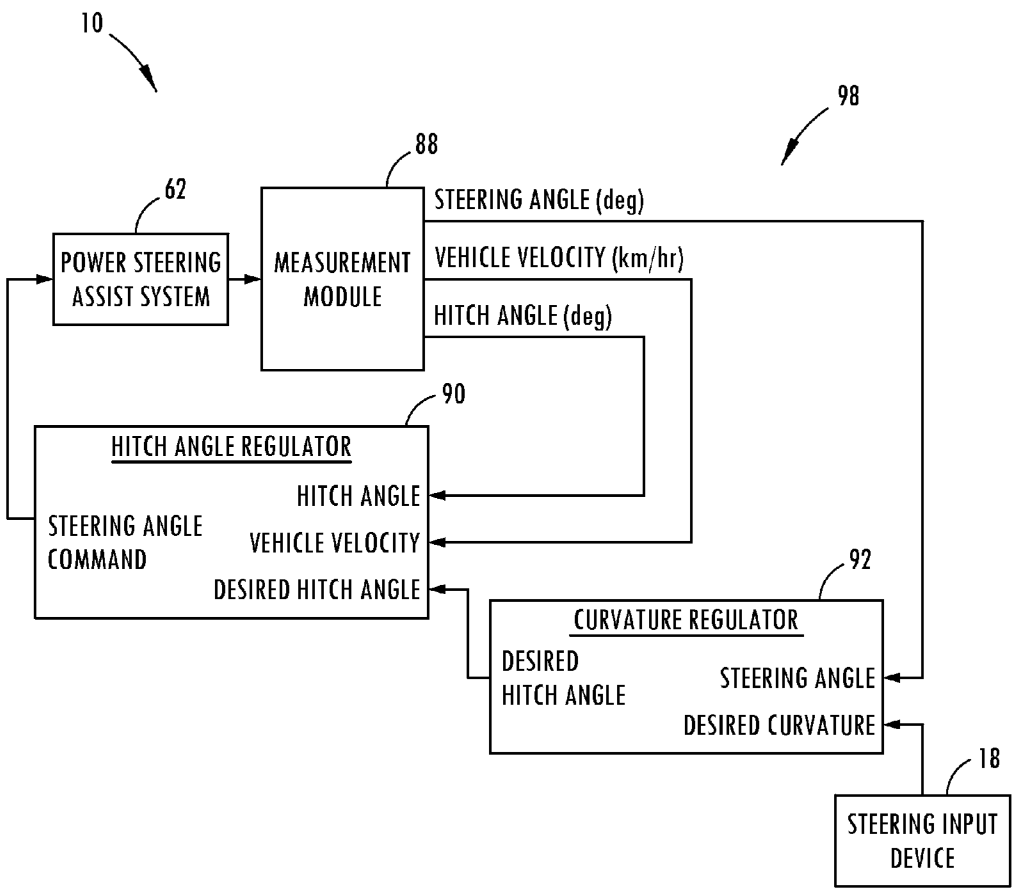

10
98
88
62
STEERING ANGLE (deg)
POWER STEERING ASSIST SYSTEM
MEASUREMENT MODULE
VEHICLE VELOCITY (km/hr)
HITCH ANGLE (deg)
90
HITCH ANGLE REGULATOR
HITCH ANGLE
STEERING ANGLE COMMAND
VEHICLE VELOCITY
DESIRED HITCH ANGLE
92
CURVATURE REGULATOR
DESIRED HITCH ANGLE
STEERING ANGLE
DESIRED CURVATURE
18
STEERING INPUT DEVICE

FIG. 4

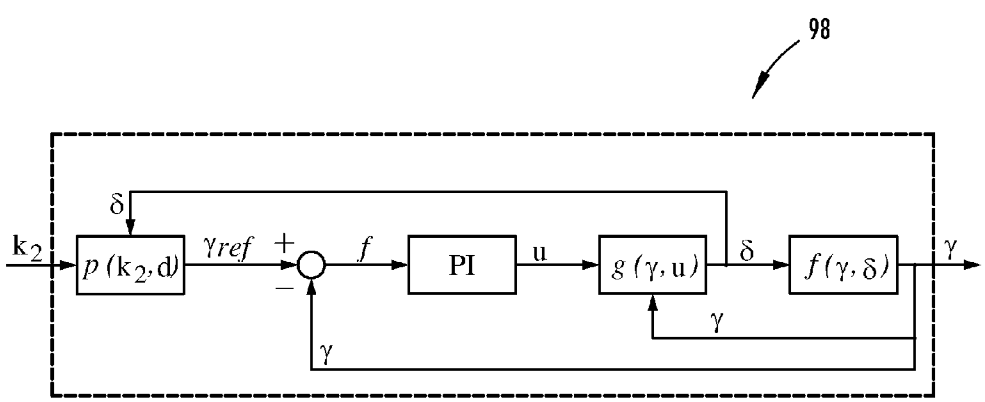

98
δ
k2
p (k2, d)
γref
+
−
f
PI
u
g (γ, u)
δ
f (γ, δ)
γ
γ
γ

FIG. 5

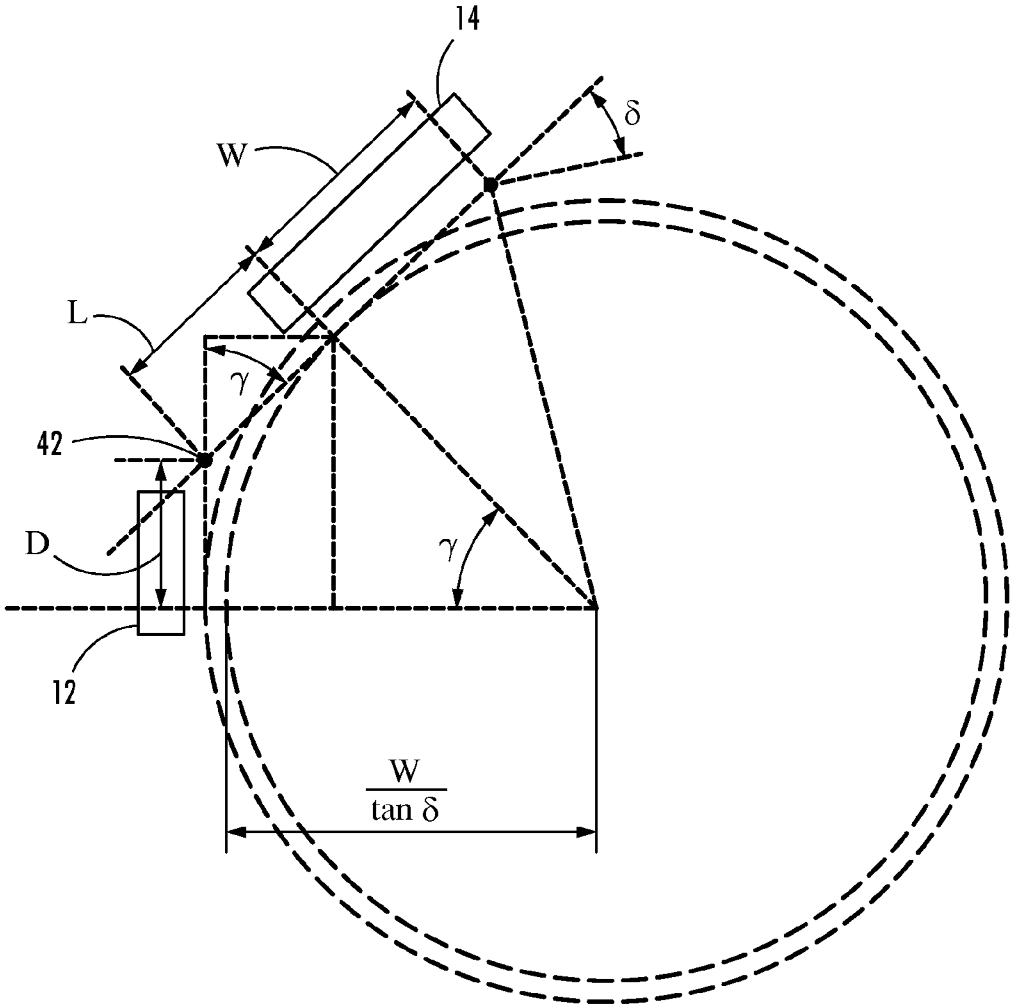
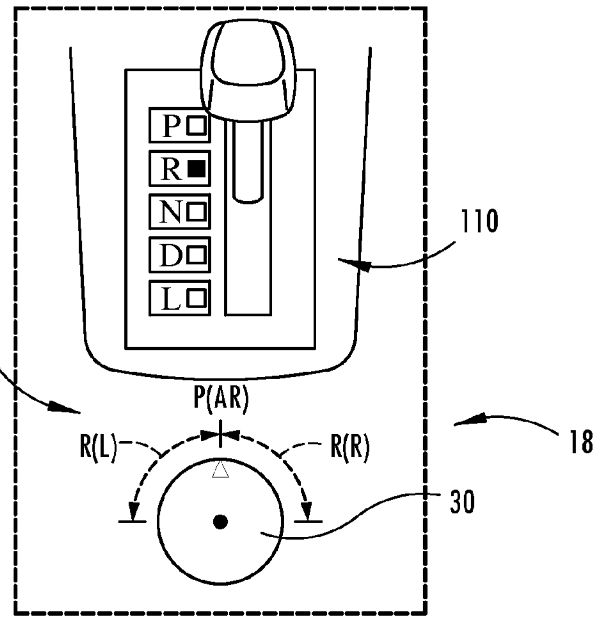
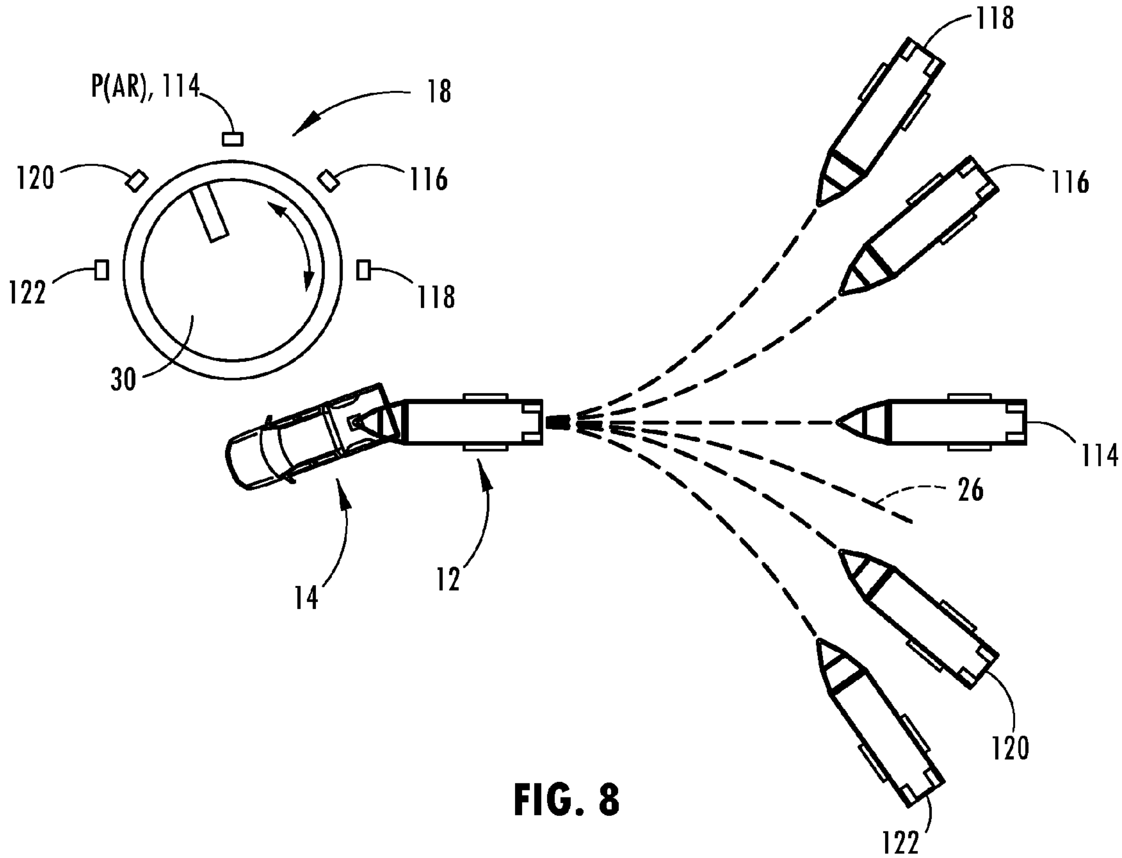


FIG. 6



P
R
N
D
L
110
108
P(AR)
R(L)
R(R)
18
30

FIG. 7



P(AR), 114
18
120
116
122
118
30
118
116
114
26
14
12
120
122

FIG. 8

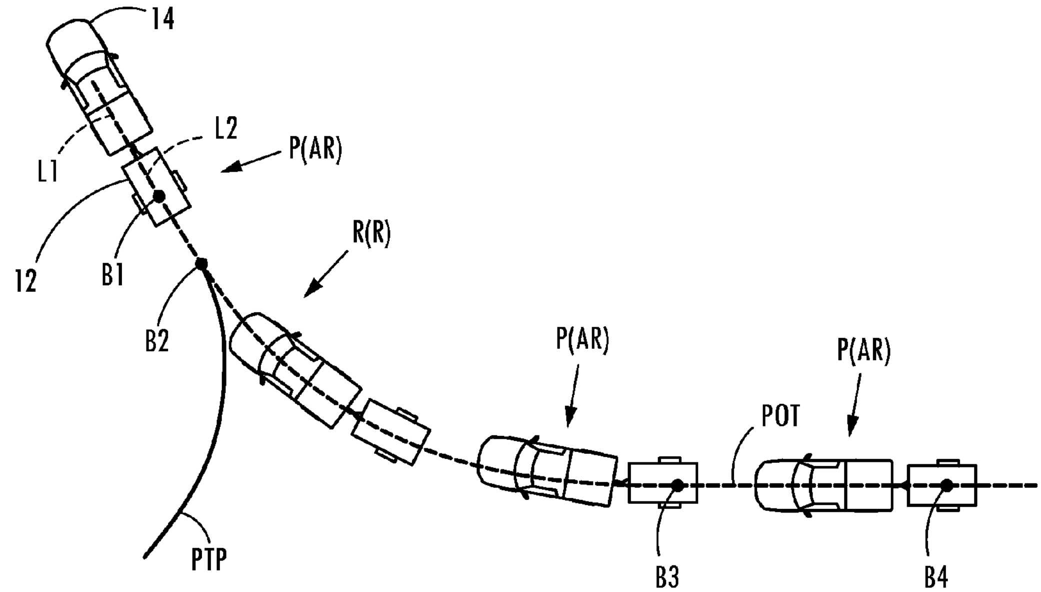

14
L2
P(AR)
L1
12
B1
R(R)
B2
P(AR)
P(AR)
POT
PTP
B3
B4

FIG. 9

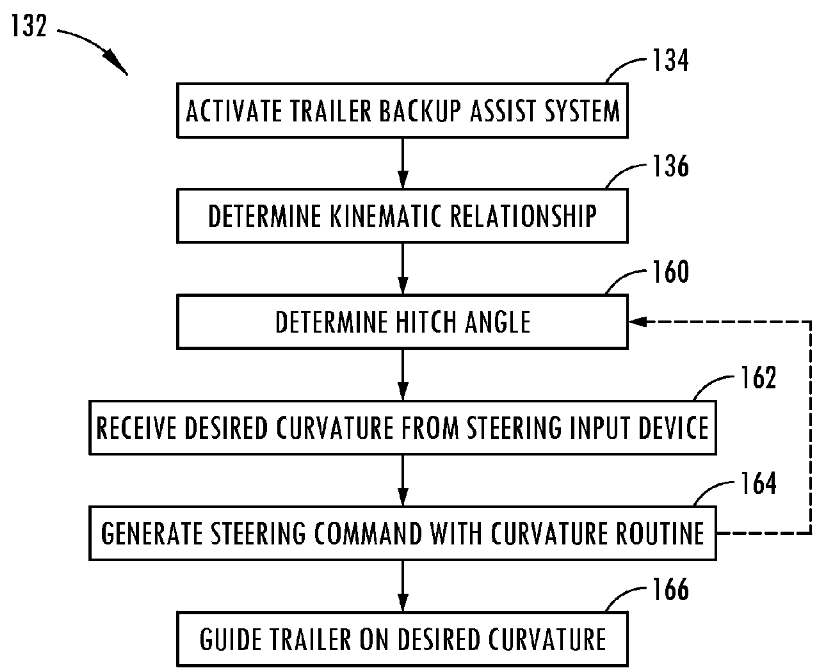

132
134
ACTIVATE TRAILER BACKUP ASSIST SYSTEM
136
DETERMINE KINEMATIC RELATIONSHIP
160
DETERMINE HITCH ANGLE
162
RECEIVE DESIRED CURVATURE FROM STEERING INPUT DEVICE
164
GENERATE STEERING COMMAND WITH CURVATURE ROUTINE
166
GUIDE TRAILER ON DESIRED CURVATURE

FIG. 10

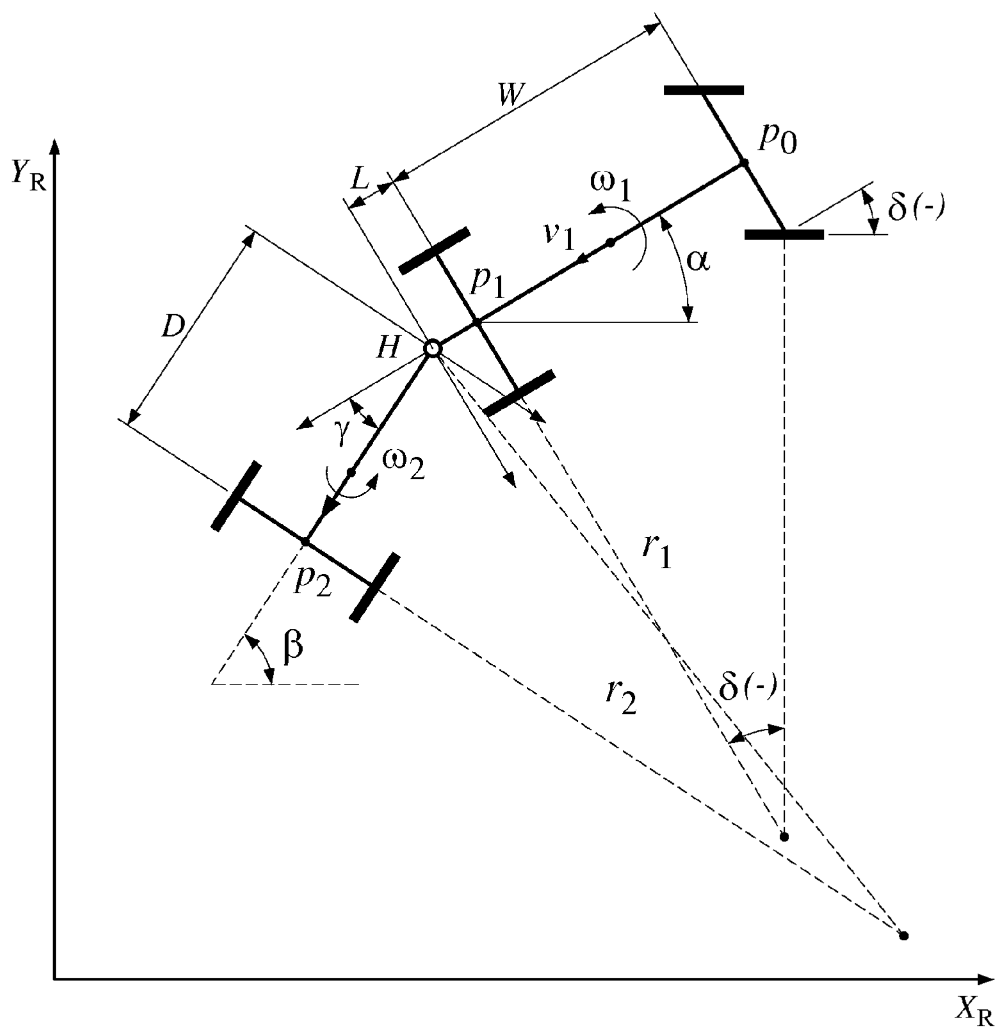

W
p_0
Y_R
L
ω_1
$\delta(-)$
v_1
α
p_1
D
H
γ
ω_2
r_1
p_2
β
r_2
$\delta(-)$
X_R

FIG. 11

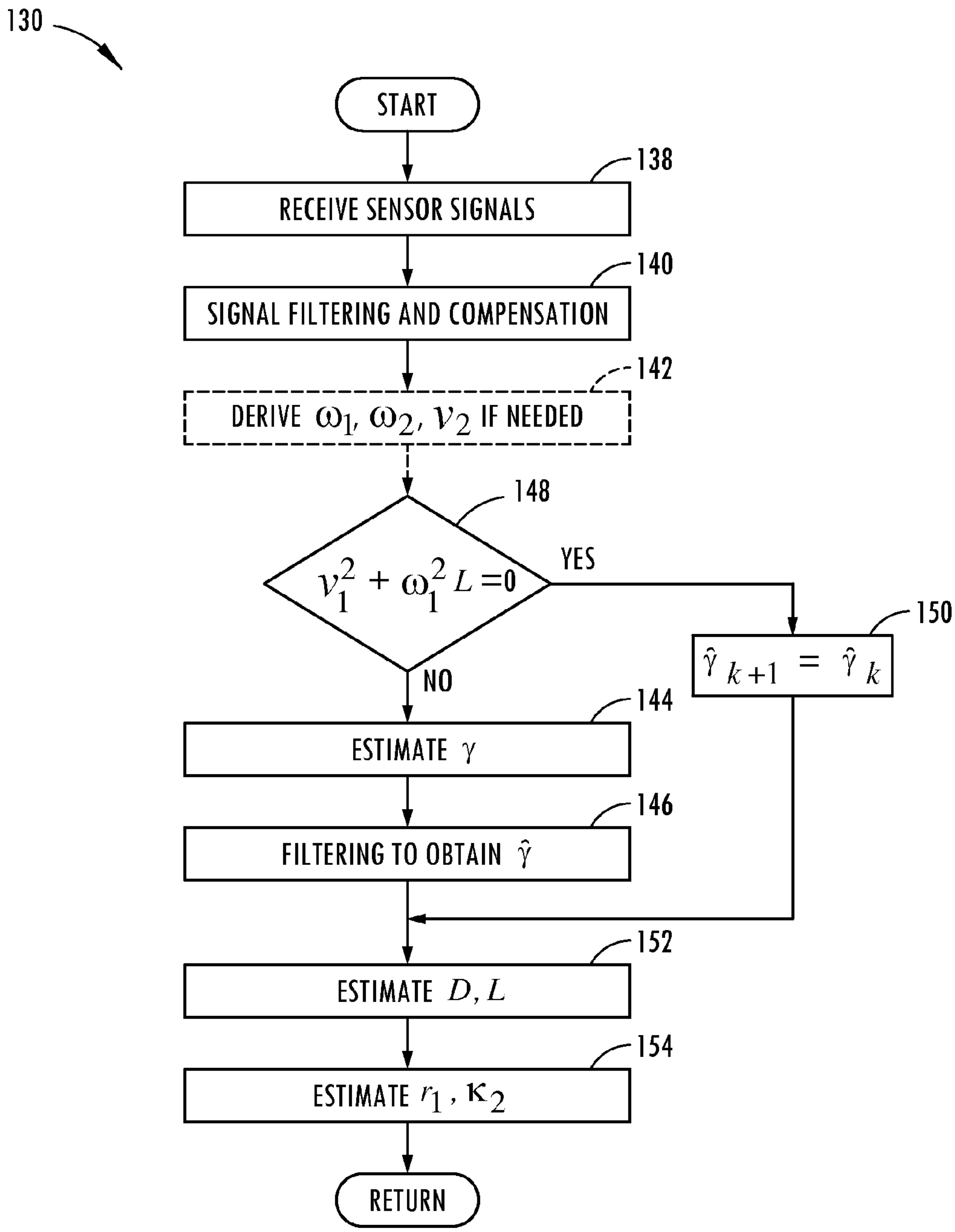

130
START
138
RECEIVE SENSOR SIGNALS
140
SIGNAL FILTERING AND COMPENSATION
142
DERIVE ω_1, ω_2, v_2 IF NEEDED
148
$v_1^2 + \omega_1^2 L = 0$
YES
NO
150
$\hat{\gamma}_{k+1} = \hat{\gamma}_k$
144
ESTIMATE γ
146
FILTERING TO OBTAIN $\hat{\gamma}$
152
ESTIMATE D, L
154
ESTIMATE r_1, κ_2
RETURN

FIG. 12

TRAILER MOTION AND PARAMETER ESTIMATION SYSTEM

FIELD OF THE INVENTION

The disclosure made herein relates generally to trailer motion and parameter estimation, and more particularly to hitch angle estimation for a trailer using yaw signals to assist with vehicle guidance of the trailer, such as a trailer backup assist system.

BACKGROUND OF THE INVENTION

Reversing a vehicle while towing a trailer can be challenging for many drivers, particularly for drivers that drive with a trailer on an infrequent basis or with various types of trailers. Systems used to assist a driver with backing a trailer frequently estimate the position of the trailer relative to the vehicle with a sensor that determines a hitch angle. The accuracy and reliability of this hitch angle estimation can be critical to the operation of the backup assist system. It is also understood that reliable hitch angle estimation can be useful for additional vehicle features, such as monitoring for trailer sway.

SUMMARY OF THE INVENTION

According to one aspect of the present invention, a trailer backup assist system for a vehicle reversing a trailer includes a trailer sensor module that generates at least one of a trailer yaw rate and a trailer speed. The trailer backup assist system also includes a vehicle sensor system that generates a vehicle yaw rate and a vehicle speed. Further, the trailer backup assist system includes a controller that estimates a hitch angle based on the vehicle yaw rate, vehicle speed, and one of the trailer yaw rate or trailer speed in view of a kinematic relationship.

According to another aspect of the present invention, a system for estimating a hitch angle between a vehicle and a trailer includes a first sensor that is coupled with the trailer for determining a trailer yaw rate. The system also includes a second sensor that is coupled with the vehicle for determining a vehicle yaw rate. Further, the system includes a controller that instantaneously estimates a hitch angle based on the trailer yaw rate and the vehicle yaw rate in view of a kinematic relationship between the trailer and the vehicle.

According to a further aspect of the present invention, a method for estimating a hitch angle between a vehicle and a trailer includes sensing a yaw rate of the trailer, sensing a yaw rate of the vehicle, and sensing a speed of the vehicle. The method also includes determining an instantaneous hitch angle based on the yaw rates of the trailer and the vehicle and the speed of the vehicle in view of a kinematic relationship between the trailer and the vehicle.

These and other aspects, objects, and features of the present invention will be understood and appreciated by those skilled in the art upon studying the following specification, claims, and appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. **1** is a top perspective view of a vehicle attached to a trailer with one embodiment of a hitch angle sensor for operating a trailer backup assist system;

FIG. **2** is a block diagram illustrating one embodiment of the trailer backup assist system having a steering input device, a curvature controller, and a trailer braking system;

FIG. **3** is a schematic diagram that illustrates the geometry of a vehicle and a trailer overlaid with a two-dimensional x-y coordinate system, identifying variables used to determine a kinematic relationship of the vehicle and the trailer for the trailer backup assist system, according to one embodiment;

FIG. **4** is a schematic block diagram illustrating portions of a curvature controller, according to an additional embodiment, and other components of the trailer backup assist system, according to such an embodiment;

FIG. **5** is schematic block diagram of the curvature controller of FIG. **4**, showing the feedback architecture and signal flow of the curvature controller, according to such an embodiment;

FIG. **6** is a schematic diagram showing a relationship between a hitch angle and a steering angle of the vehicle as it relates to curvature of the trailer and a jackknife angle;

FIG. **7** is a plan view of a steering input device having a rotatable knob for operating the trailer backup assist system, according to one embodiment;

FIG. **8** is a plan view of another embodiment of a rotatable knob for selecting a desired curvature of a trailer and a corresponding schematic diagram illustrating a vehicle and a trailer with various trailer curvature paths correlating with desired curvatures that may be selected;

FIG. **9** is a schematic diagram showing a backup sequence of a vehicle and a trailer implementing various curvature selections with the trailer backup assist system, according to one embodiment;

FIG. **10** is a flow diagram illustrating a method of operating a trailer backup assist system using an operating routine for steering a vehicle reversing a trailer with normalized control of the desired curvature, according to one embodiment;

FIG. **11** is a schematic diagram that illustrates the geometry of a vehicle and a trailer overlaid with a two-dimensional x-y coordinate system, identifying variables used to determine a hitch angle, according to one embodiment; and

FIG. **12** is a flow diagram illustrating a method of estimating a hitch angle using a hitch angle estimation routine, according to one embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

For purposes of description herein, it is to be understood that the disclosed trailer backup assist system and the related methods may assume various alternative embodiments and orientations, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. While various aspects of the trailer backup assist system and the related methods are described with reference to a particular illustrative embodiment, the disclosed invention is not limited to such embodiments, and additional modifications, applications, and embodiments may be implemented without departing from the disclosed invention. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

Referring to FIGS. **1-12**, reference numeral **10** generally designates a trailer backup assist system for controlling a backing path of a trailer **12** attached to a vehicle **14** by allowing a driver of the vehicle **14** to specify a desired curvature **26** of the backing path of the trailer **12**. In one embodiment, the trailer backup assist system **10** automatically steers the vehicle **14** to guide the trailer **12** on the desired curvature or backing path **26** as a driver uses the accelerator and brake pedals to control the reversing speed of the vehicle **14**. To monitor the position of the trailer **12** relative to the vehicle **14**, the trailer backup assist system **10** may include a sensor system **16** that senses or otherwise determines a hitch angle γ between the trailer **12** and the vehicle **14**. In one embodiment, the sensor system **16** may include a sensor module **20** attached to the trailer **12** that monitors the dynamics of the trailer **12**, such as yaw rate, and communicates with a controller **28** of the trailer backup assist system **10** to determine the instantaneous hitch angle γ. Accordingly, one embodiment of a sensor module **20** is adapted to attach to the trailer **12** and generate a trailer yaw rate ω_2. The trailer backup assist system **10** according to such an embodiment may also include a vehicle sensor system **17** that generates a vehicle yaw rate ω_1 and a vehicle speed v_1. The controller **28** of the trailer backup assist system **10** may thereby estimates a hitch angle γ based on the trailer yaw rate ω_2, the vehicle yaw rate ω_1, and the vehicle speed v_1 in view of a kinematic relationship between the trailer **12** and the vehicle **14**. In another embodiment, the sensor system **16** may include a hitch angle sensor **44**, such as a vision-based system that employs a camera **46** on the vehicle **14** to monitor a target **52** on the trailer **12** to determine the hitch angle γ and thereby further increase reliability of the overall estimated hitch angle γ.

With respect to the general operation of the trailer backup assist system **10**, a steering input device **18** may be provided, such as a rotatable knob **30**, for a driver to provide the desired curvature **26** of the trailer **12**. As such, the steering input device **18** may be operable between a plurality of selections, such as successive rotated positions of a knob **30**, that each provide an incremental change to the desired curvature **26** of the trailer **12**. Upon inputting the desired curvature **26**, the controller may generate a steering command for the vehicle **14** to guide the trailer **12** on the desired curvature **26** based on the estimated hitch angle γ and a kinematic relationship between the trailer **12** and the vehicle **14**. Therefore, the accuracy of the hitch angle estimation is critical to operating the trailer backup assist system **10**. However, it is appreciated that such a system for instantaneously estimating hitch angle may be used in association with additional or alternative vehicle features, such as trailer sway monitoring.

With reference to the embodiment shown in FIG. **1**, the vehicle **14** is a pickup truck embodiment that is equipped with one embodiment of the trailer backup assist system **10** for controlling the backing path of the trailer **12** that is attached to the vehicle **14**. Specifically, the vehicle **14** is pivotally attached to one embodiment of the trailer **12** that has a box frame **32** with an enclosed cargo area **34**, a single axle having a right wheel assembly and a left wheel assembly, and a tongue **36** longitudinally extending forward from the enclosed cargo area **34**. The illustrated trailer **12** also has a trailer hitch connector in the form of a coupler assembly **38** that is connected to a vehicle hitch connector in the form of a hitch ball **40**. The coupler assembly **38** latches onto the hitch ball **40** to provide a pivoting ball joint connection **42** that allows for articulation of the hitch angle γ. It should be appreciated that additional embodiments of the trailer **12** may alternatively couple with the vehicle **14** to provide a pivoting connection, such as by connecting with a fifth wheel connector. It is also contemplated that additional embodiments of the trailer may include more than one axle and may have various shapes and sizes configured for different loads and items, such as a boat trailer or a flatbed trailer.

Still referring to FIG. **1**, the sensor system **16** in the illustrated embodiment includes both a sensor module **20** and a vision-based hitch angle sensor **44** for estimating the hitch angle γ between the vehicle **14** and the trailer **12**. The illustrated hitch angle sensor **44** employs a camera **46** (e.g. video imaging camera) that may be located proximate an upper region of the vehicle tailgate **48** at the rear of the vehicle **14**, as shown, such that the camera **46** may be elevated relative to the tongue **36** of the trailer **12**. The illustrated camera **46** has an imaging field of view **50** located and oriented to capture one or more images of the trailer **12**, including a region containing one or more desired target placement zones for at least one target **52** to be secured. Although it is contemplated that the camera **46** may capture images of the trailer **12** without a target **52** to determine the hitch angle γ, in the illustrated embodiment, the trailer backup assist system **10** includes a target **52** placed on the trailer **12** to allow the trailer backup assist system **10** to utilize information acquired via image acquisition and processing of the target **52**. For instance, the illustrated camera **46** may include a video imaging camera that repeatedly captures successive images of the trailer **12** that may be processed to identify the target **52** and its location on the trailer **12** for determining movement of the target **52** and the trailer **12** relative to the vehicle **14** and the corresponding hitch angle γ. It should also be appreciated that the camera **46** may include one or more video imaging cameras and may be located at other locations on the vehicle **14** to acquire images of the trailer **12** and the desired target placement zone, such as on a passenger cab **54** of the vehicle **14** to capture images of a gooseneck trailer. Furthermore, it is contemplated that additional embodiments of the hitch angle sensor **44** and the sensor system **16** for providing the hitch angle γ may include one or a combination of a potentiometer, a magnetic-based sensor, an optical sensor, a proximity sensor, a rotational sensor, a capacitive sensor, an inductive sensor, or a mechanical based sensor, such as a mechanical sensor assembly mounted to the pivoting ball joint connection **42**, energy transducers of a reverse aid system, a blind spot system, and/or a cross traffic alert system, and other conceivable sensors or indicators of the hitch angle γ to supplement or be used in place of the vision-based hitch angle sensor **44**.

The embodiment of the sensor module **20** illustrated in FIG. **1** includes a housed sensor cluster **21** mounted on the tongue **36** of the trailer **12** proximate the enclosed cargo area **34** and includes left and right wheel speed sensors **23** on laterally opposing wheels of the trailer **12**. It is conceivable that the wheel speed sensors **23** may be bi-directional wheel speed sensors for monitoring both forward and reverse speeds. Also, it is contemplated that the sensor cluster **21** in additional embodiments may be mounted on alternative portions of the trailer **12**.

The sensor module **20** generates a plurality of signals indicative of various dynamics of the trailer **12**. The signals may include a yaw rate signal, a lateral acceleration signal, and wheel speed signals generated respectively by a yaw rate sensor **25**, an accelerometer **27**, and the wheel speed sensors **23**. Accordingly, in the illustrated embodiment, the yaw rate sensor **25** and the accelerometer **27** are contained within the housed sensor cluster **21**, although other configurations are conceivable. It is conceivable that the accelerometer **27**, in some embodiments, may be two or more separate sensors and may be arranged at an offset angle, such as two sensors arranged at plus and minus forty-five degrees from the longitudinal direction of the trailer or arranged parallel with the longitudinal and lateral directions of the trailer, to generate a more robust acceleration signal. It is also contemplated that these sensor signals could be compensated and filtered to remove offsets or drifts, and smooth out noise. Further, the controller **28** may utilizes processed signals received outside of the sensor system **16**, including standard signals from the brake control system **72** and the power assist steering system **62**, such as vehicle yaw rate ω_1, vehicle speed v_1, and steering angle **6**, to estimate the trailer hitch angle γ, trailer speed, and related trailer parameters. As described in more detail below, the controller **28** may estimate the hitch angle γ based on the trailer yaw rate ω_2, the vehicle yaw rate ω_1, and the vehicle speed v_1 in view of a kinematic relationship between the trailer **12** and the vehicle **14**. The controller **28** of the trailer backup assist system **10** may also utilize the estimated trailer variables and trailer parameters to control the steering system **62**, brake control system **72**, and the powertrain control system **74**, such as to assist backing the vehicle-trailer combination or to mitigate a trailer sway condition.

With reference to the embodiment of the trailer backup assist system **10** shown in FIG. **2**, the hitch angle sensor **44** is provided in dashed lines to illustrate that in some embodiments it may be omitted when the trailer sensor module **20** is provided. The illustrated embodiment of the trailer backup assist system **10** receives vehicle and trailer status-related information from additional sensors and devices. This information includes positioning information from a positioning device **56**, which may include a global positioning system (GPS) on the vehicle **14** or a handled device, to determine a coordinate location of the vehicle **14** and the trailer **12** based on the location of the positioning device **56** with respect to the trailer **12** and/or the vehicle **14** and based on the estimated hitch angle γ. The positioning device **56** may additionally or alternatively include a dead reckoning system for determining the coordinate location of the vehicle **14** and the trailer **12** within a localized coordinate system based at least on vehicle speed, steering angle, and hitch angle γ. Other vehicle information received by the trailer backup assist system **10** may include a speed of the vehicle **14** from a speed sensor **58** and a yaw rate of the vehicle **14** from a yaw rate sensor **60**. It is contemplated that in additional embodiments, the hitch angle sensor **44** and other vehicle sensors and devices may provide sensor signals or other information, such as proximity sensor signals or successive images of the trailer **12**, that the controller of the trailer backup assist system **10** may process with various routines to determine an indicator of the hitch angle γ, such as a range of hitch angles.

As further shown in FIG. **2**, one embodiment of the trailer backup assist system **10** is in communication with a power assist steering system **62** of the vehicle **14** to operate the steered wheels **64** (FIG. **1**) of the vehicle **14** for moving the vehicle **14** in such a manner that the trailer **12** reacts in accordance with the desired curvature **26** of the trailer **12**. In the illustrated embodiment, the power assist steering system **62** is an electric power-assisted steering (EPAS) system that includes an electric steering motor **66** for turning the steered wheels **64** to a steering angle based on a steering command, whereby the steering angle may be sensed by a steering angle sensor **67** of the power assist steering system **62**. The steering command may be provided by the trailer backup assist system **10** for autonomously steering during a backup maneuver and may alternatively be provided manually via a rotational position (e.g., steering wheel angle) of a steering wheel **68** (FIG. **1**). However, in the illustrated embodiment, the steering wheel **68** of the vehicle **14** is mechanically coupled with the steered wheels **64** of the vehicle **14**, such that the steering wheel **68** moves in concert with steered wheels **64**, preventing manual intervention with the steering wheel **68** during autonomous steering. More specifically, a torque sensor **70** is provided on the power assist steering system **62** that senses torque on the steering wheel **68** that is not expected from autonomous control of the steering wheel **68** and therefore indicative of manual intervention, whereby the trailer backup assist system **10** may alert the driver to discontinue manual intervention with the steering wheel **68** and/or discontinue autonomous steering.

In alternative embodiments, some vehicles have a power assist steering system **62** that allows a steering wheel **68** to be partially decoupled from movement of the steered wheels **64** of such a vehicle. Accordingly, the steering wheel **68** can be rotated independent of the manner in which the power assist steering system **62** of the vehicle controls the steered wheels **64** (e.g., autonomous steering as commanded by the trailer backup assist system **10**). As such, in these types of vehicles where the steering wheel **68** can be selectively decoupled from the steered wheels **64** to allow independent operation thereof, the steering wheel **68** may be used as a steering input device **18** for the trailer backup assist system **10**, as disclosed in greater detail herein.

Referring again to the embodiment illustrated in FIG. **2**, the power assist steering system **62** provides the controller **28** of the trailer backup assist system **10** with information relating to a rotational position of steered wheels **64** of the vehicle **14**, including a steering angle. The controller **28** in the illustrated embodiment processes the current steering angle, in addition to other vehicle **14** and trailer **12** conditions to guide the trailer **12** along the desired curvature **26**. It is conceivable that the trailer backup assist system **10**, in additional embodiments, may be an integrated component of the power assist steering system **62**. For example, the power assist steering system **62** may include a trailer backup assist algorithm for generating vehicle steering information and commands as a function of all or a portion of information received from the steering input device **18**, the hitch angle sensor **44**, the power assist steering system **62**, a vehicle brake control system **72**, a powertrain control system **74**, and other vehicle sensors and devices.

As also illustrated in FIG. **2**, the vehicle brake control system **72** may also communicate with the controller **28** to provide the trailer backup assist system **10** with braking information, such as vehicle wheel speed, and to receive braking commands from the controller **28**. For instance, vehicle speed information can be determined from individual wheel speeds as monitored by the brake control system **72**. Vehicle speed may also be determined from the powertrain control system **74**, the speed sensor **58**, and the positioning device **56**, among other conceivable means. In some embodiments, individual wheel speeds can also be used to determine a vehicle yaw rate, which can be provided to the trailer backup assist system **10** in the alternative or in addition to the vehicle yaw rate sensor **60**. In certain embodiments, the trailer backup assist system **10** can provide vehicle braking information to the brake control system **72** for allowing the trailer backup assist system **10** to control braking of the vehicle **14** during backing of the trailer **12**. For example, the trailer backup assist system **10** in some embodiments may regulate speed of the vehicle **14** during backing of the trailer **12**, which can reduce the potential for unacceptable trailer backup conditions. Examples of unacceptable trailer backup conditions include, but are not limited to, a vehicle **14** over speed condition, a high hitch angle rate, trailer angle dynamic instability, a calculated theoretical trailer jackknife condition (defined by a maximum vehicle steering angle, drawbar length, tow vehicle wheelbase, and an effective trailer length), or physical contact jackknife limitation (defined by an angular displacement limit relative to the vehicle **14** and the trailer **12**), and the like. It is disclosed herein that the trailer backup assist system **10** can issue an alert signal corresponding to a notification of an actual, impending, and/or anticipated unacceptable trailer backup condition.

The powertrain control system **74**, as shown in the embodiment illustrated in FIG. **2**, may also interact with the trailer backup assist system **10** for regulating speed and acceleration of the vehicle **14** during backing of the trailer **12**. As mentioned above, regulation of the speed of the vehicle **14** may be necessary to limit the potential for unacceptable trailer backup conditions such as, for example, jackknifing and trailer angle dynamic instability. Similar to high-speed considerations as they relate to unacceptable trailer backup conditions, high acceleration and high dynamic driver curvature requests can also lead to such unacceptable trailer backup conditions.

With continued reference to FIG. **2**, the trailer backup assist system **10** in the illustrated embodiment may communicate with one or more devices, including a vehicle alert system **76**, which may prompt visual, auditory, and tactile warnings. For instance, vehicle brake lights **78** and vehicle emergency flashers may provide a visual alert and a vehicle horn **79** and/or speaker **81** may provide an audible alert. Additionally, the trailer backup assist system **10** and/or vehicle alert system **76** may communicate with a human machine interface (HMI) **80** for the vehicle **14**. The HMI **80** may include a vehicle display **82**, such as a center-stack mounted navigation or entertainment display (FIG. **1**). Further, the trailer backup assist system **10** may communicate via wireless communication with another embodiment of the HMI **80**, such as with one or more handheld or portable devices, including one or more smartphones. The portable device may also include the display **82** for displaying one or more images and other information to a user. For instance, the portable device may display one or more images of the trailer **12** and an indication of the estimated hitch angle on the display **82**. In addition, the portable device may provide feedback information, such as visual, audible, and tactile alerts.

As further illustrated in FIG. **2**, the trailer backup assist system **10** includes a steering input device **18** that is connected to the controller **28** for allowing communication of information therebetween. It is disclosed herein that the steering input device **18** can be coupled to the controller **28** in a wired or wireless manner. The steering input device **18** provides the trailer backup assist system **10** with information defining the desired backing path of travel of the trailer **12** for the controller **28** to process and generate steering commands. More specifically, the steering input device **18** may provide a selection or positional information that correlates with a desired curvature **26** of the desired backing path of travel of the trailer **12**. Also, the trailer steering commands provided by the steering input device **18** can include information relating to a commanded change in the path of travel, such as an incremental change in the desired curvature **26**, and information relating to an indication that the trailer **12** is to travel along a path defined by a longitudinal centerline axis of the trailer **12**, such as a desired curvature value of zero that defines a substantially straight path of travel for the trailer. As will be discussed below in more detail, the steering input device **18** according to one embodiment may include a movable control input device for allowing a driver of the vehicle **14** to command desired trailer steering actions or otherwise select and alter a desired curvature. For instance, the moveable control input device may be a rotatable knob **30**, which can be rotatable about a rotational axis extending through a top surface or face of the knob **30**. In other embodiments, the rotatable knob **30** may be rotatable about a rotational axis extending substantially parallel to a top surface or face of the rotatable knob **30**. Furthermore, the steering input device **18**, according to additional embodiments, may include alternative devices for providing a desired curvature **26** or other information defining a desired backing path, such as a joystick, a keypad, a series of depressible buttons or switches, a sliding input device, various user interfaces on a touch-screen display, a vision based system for receiving gestures, a control interface on a portable device, and other conceivable input devices as generally understood by one having ordinary skill in the art. It is contemplated that the steering input device **18** may also function as an input device for other features, such as providing inputs for other vehicle features or systems.

Still referring to the embodiment shown in FIG. **2**, the controller **28** is configured with a microprocessor **84** to process logic and routines stored in memory **86** that receive information from the sensor system **16**, including the trailer sensor module **20**, the hitch angle sensor **44**, the steering input device **18**, the power assist steering system **62**, the vehicle brake control system **72**, the trailer braking system, the powertrain control system **74**, and other vehicle sensors and devices. The controller **28** may generate vehicle steering information and commands as a function of all or a portion of the information received. Thereafter, the vehicle steering information and commands may be provided to the power assist steering system **62** for affecting steering of the vehicle **14** to achieve a commanded path of travel for the trailer **12**. The controller **28** may include the microprocessor **84** and/or other analog and/or digital circuitry for processing one or more routines. Also, the controller **28** may include the memory **86** for storing one or more routines, including a hitch angle estimation routine **130**, an operating routine **132**, and a curvature routine **98**. It should be appreciated that the controller **28** may be a stand-alone dedicated controller or may be a shared controller integrated with other control functions, such as integrated with the sensor system **16**, the power assist steering system **62**, and other conceivable onboard or off-board vehicle control systems.

With reference to FIG. **3**, we now turn to a discussion of vehicle and trailer information and parameters used to calculate a kinematic relationship between a curvature of a path of travel of the trailer **12** and the steering angle of the vehicle **14** towing the trailer **12**, which can be desirable for a trailer backup assist system **10** configured in accordance with some embodiments, including for use by a curvature routine **98** of the controller **28** in one embodiment. To achieve such a kinematic relationship, certain assumptions may be made with regard to parameters associated with the vehicle/trailer system. Examples of such assumptions include, but are not limited to, the trailer **12** being backed by the vehicle **14** at a relatively low speed, wheels of the vehicle **14** and the trailer **12** having negligible (e.g., no) slip, tires of the vehicle **14** having negligible (e.g., no) lateral compliance, tires of the vehicle **14** and the trailer **12** having negligible (e.g., no) deformation, actuator dynamics of the vehicle **14** being negligible, and the vehicle **14** and the trailer **12** exhibiting negligible (e.g., no) roll or pitch motions, among other conceivable factors with the potential to have an effect on controlling the trailer **12** with the vehicle **14**.

As shown in FIG. **3**, for a system defined by a vehicle **14** and a trailer **12**, the kinematic relationship is based on various parameters associated with the vehicle **14** and the trailer **12**. These parameters include:

δ: steering angle at steered front wheels of the vehicle;

α: yaw angle of the vehicle;

β: yaw angle of the trailer;

γ: hitch angle ($\gamma=\beta-\alpha$);

W: wheel base of the vehicle;

L: drawbar length between hitch point and rear axle of the vehicle;

D: distance (trailer length) between hitch point and axle of the trailer or effective axle for a multiple axle trailer; and

r_2: curvature radius for the trailer.

One embodiment of a kinematic relationship between trailer path radius of curvature r_2 at the midpoint of an axle of the trailer **12**, steering angle δ of the steered wheels **64** of the vehicle **14**, and the hitch angle γ can be expressed in the equation provided below. As such, if the hitch angle γ is provided, the trailer path curvature κ_2 can be controlled based on regulating the steering angle δ (where $\dot{\beta}$ is trailer yaw rate and $\dot{\eta}$ is trailer velocity).

$$\kappa_2 = \frac{1}{r_2} = \frac{\dot{\beta}}{\dot{\eta}} = \frac{\left(W + \frac{KV^2}{g}\right)\sin\gamma + L\cos\gamma\tan\delta}{D\left(\left(W + \frac{KV^2}{g}\right)\cos\gamma - L\sin\gamma\tan\delta\right)}$$

This relationship can be expressed to provide the steering angle δ as a function of trailer path curvature κ_2 and hitch angle γ.

$$\delta = \tan^{-1}\left(\frac{\left(W + \frac{KV^2}{g}\right)[\kappa_2 D\cos\gamma - \sin\gamma]}{DL\kappa_2\sin\gamma + L\sin c\cos\gamma}\right) = F(\gamma, \kappa_2, K)$$

Accordingly, for a particular vehicle and trailer combination, certain parameters (e.g., D, W and L) of the kinematic relationship are constant and assumed known. V is the vehicle longitudinal speed and g is the acceleration due to gravity. K is a speed dependent parameter which when set to zero makes the calculation of steering angle independent of vehicle speed. For example, vehicle-specific parameters of the kinematic relationship can be predefined in an electronic control system of the vehicle **14** and trailer-specific parameters of the kinematic relationship can be inputted by a driver of the vehicle **14**, determined from sensed trailer behavior in response to vehicle steering commands, or otherwise determined from signals provided by the trailer **12**. Trailer path curvature κ_2 can be determined from the driver input via the steering input device **18**. Through the use of the equation for providing steering angle, a corresponding steering command can be generated by the curvature routine **98** for controlling the power assist steering system **62** of the vehicle **14**.

In an additional embodiment, an assumption may be made by the curvature routine **98** that a longitudinal distance L between the pivoting connection and the rear axle of the vehicle **14** is equal to zero for purposes of operating the trailer backup assist system **10** when a gooseneck trailer or other similar trailer is connected with the a hitch ball or a fifth wheel connector located over a rear axle of the vehicle **14**. The assumption essentially assumes that the pivoting connection with the trailer **12** is substantially vertically aligned with the rear axle of the vehicle **14**. When such an assumption is made, the controller **28** may generate the steering angle command for the vehicle **14** as a function independent of the longitudinal distance L between the pivoting connection and the rear axle of the vehicle **14**. It is appreciated that the gooseneck trailer mentioned generally refers to the tongue configuration being elevated to attach with the vehicle **14** at an elevated location over the rear axle, such as within a bed of a truck, whereby embodiments of the gooseneck trailer may include flatbed cargo areas, enclosed cargo areas, campers, cattle trailers, horse trailers, lowboy trailers, and other conceivable trailers with such a tongue configuration.

Yet another embodiment of the curvature routine **98** of the trailer backup assist system **10** is illustrated in FIG. **4**, showing the general architectural layout whereby a measurement module **88**, a hitch angle regulator **90**, and a curvature regulator **92** are routines that may be stored in the memory **86** of the controller **28**. In the illustrated layout, the steering input device **18** provides a desired curvature κ_2 value to the curvature regulator **92** of the controller **28**, which may be determined from the desired backing path **26** that is input with the steering input device **18**. The curvature regulator **92** computes a desired hitch angle γ(d) based on the current desired curvature κ_2 along with the steering angle δ provided by a measurement module **88** in this embodiment of the controller **28**. The measurement module **88** may be a memory device separate from or integrated with the controller **28** that stores data from sensors of the trailer backup assist system **10**, such as the hitch angle sensor **44**, the vehicle speed sensor **58**, the steering angle sensor, or alternatively the measurement module **88** may otherwise directly transmit data from the sensors without functioning as a memory device. Once the desired hitch angle γ(d) is computed by the curvature regulator **92** the hitch angle regulator **90** generates a steering angle command based on the computed desired hitch angle γ(d) as well as a measured or otherwise estimated hitch angle γ(m) and a current velocity of the vehicle **14**. The steering angle command is supplied to the power assist steering system **62** of the vehicle **14**, which is then fed back to the measurement module **88** to reassess the impacts of other vehicle characteristics impacted from the implementation of the steering angle command or other changes to the system. Accordingly, the curvature regulator **92** and the hitch angle regulator **90** continually process information from the measurement module **88** to provide accurate steering angle commands that place the trailer **12** on the desired curvature κ_2 and the desired backing path **26**, without substantial overshoot or continuous oscillation of the path of travel about the desired curvature κ_e.

As also shown in FIG. **5**, the embodiment of the curvature routine **98** shown in FIG. **4** is illustrated in a control system block diagram. Specifically, entering the control system is an input, κ_2, which represents the desired curvature **26** of the trailer **12** that is provided to the curvature regulator **92**. The curvature regulator **92** can be expressed as a static map, $p(\kappa_2, \delta)$, which in one embodiment is the following equation:

$$p(\kappa_2, \delta) = \tan^{-1}\left(\frac{\kappa_2 D + L\tan(\delta)}{\kappa_2 DL\tan(\delta) - W}\right)$$

Where,

κ_2 represents the desired curvature of the trailer **12** or $1/r_2$ as shown in FIG. **3**;

δ represents the steering angle;

L represents the distance from the rear axle of the vehicle **14** to the hitch pivot point;

D represents the distance from the hitch pivot point to the axle of the trailer **12**; and

W represents the distance from the rear axle to the front axle of the vehicle **14**.

With further reference to FIG. **5**, the output hitch angle of $p(\kappa_2, \delta)$ is provided as the reference signal, γ_{ref}, for the remainder of the control system, although the steering angle δ value used by the curvature regulator **92** is feedback from the non-linear function of the hitch angle regulator **90**. It is shown that the hitch angle regulator **90** uses feedback linearization for defining a feedback control law, as follows:

$$g(u,\gamma,v)=\delta=\tan^{-1}\left(\frac{W}{v\left(1+\frac{L}{D}\cos(\gamma)\right)}\left(u-\frac{v}{D}\sin(\gamma)\right)\right)$$

As also shown in FIG. **5**, the feedback control law, g(u, γ, v), is implemented with a proportional integral (PI) controller, whereby the integral portion substantially eliminates steady-state tracking error. More specifically, the control system illustrated in FIG. **5** may be expressed as the following differential-algebraic equations:

$$\dot{\gamma}(t)=\frac{v(t)}{D}\sin(\gamma(t))+\left(1+\frac{L}{D}\cos(\gamma(t))\right)\frac{v(t)}{W}\overline{\delta}$$

$$\tan(\delta)=\overline{\delta}=\frac{W}{v(t)\left(1+\frac{L}{D}\cos(\gamma(t))\right)}\left(K_P(p(\kappa_2,\delta)-\gamma(t))-\frac{v(t)}{D}\sin(\gamma(t))\right)$$

It is contemplated that the PI controller may have gain terms based on trailer length D since shorter trailers will generally have faster dynamics. In addition, the hitch angle regulator **90** may be configured to prevent the desired hitch angle γ(d) to reach or exceed a jackknife angle γ(j), as computed by the controller or otherwise determined by the trailer backup assist system **10**, as disclosed in greater detail herein.

Referring now to FIG. **6**, in the illustrated embodiments of the disclosed subject matter, it is desirable to limit the potential for the vehicle **14** and the trailer **12** to attain a jackknife angle (i.e., the vehicle/trailer system achieving a jackknife condition). A jackknife angle γ(j) refers to a hitch angle γ that while backing cannot be overcome by the maximum steering input for a vehicle such as, for example, the steered front wheels of the vehicle **14** being moved to a maximum steered angle δ at a maximum rate of steering angle change. The jackknife angle γ(j) is a function of a maximum wheel angle for the steered wheels of the vehicle **14**, the wheel base W of the vehicle **14**, the distance L between hitch point and the rear axle of the vehicle **14**, and the trailer length D between the hitch point and the axle of the trailer **12** or the effective axle when the trailer **12** has multiple axles. When the hitch angle γ for the vehicle **14** and the trailer **12** achieves or exceeds the jackknife angle γ(j), the vehicle **14** may be pulled forward to reduce the hitch angle γ. Thus, for limiting the potential for a vehicle/trailer system attaining a jackknife angle, it is preferable to control the yaw angle of the trailer **12** while keeping the hitch angle γ of the vehicle/trailer system relatively small.

A kinematic model representation of the vehicle **14** and the trailer **12** can also be used to determine a jackknife angle for the vehicle-trailer combination. Accordingly, with reference to FIGS. **3** and **6**, a steering angle limit for the steered front wheels requires that the hitch angle γ cannot exceed the jackknife angle γ(j), which is also referred to as a critical hitch angle γ. Thus, under the limitation that the hitch angle γ cannot exceed the jackknife angle γ(j), the jackknife angle γ(j) is the hitch angle γ that maintains a circular motion for the vehicle/trailer system when the steered wheels **64** are at a maximum steering angle δ(max). The steering angle for circular motion with hitch angle γ is defined by the following equation.

$$\tan\delta_{max}=\frac{w\sin\gamma_{max}}{D+L\cos\gamma_{max}}$$

Solving the above equation for hitch angle γ allows jackknife angle γ(j) to be determined. This solution, which is shown in the following equation, can be used in implementing trailer backup assist functionality in accordance with the disclosed subject matter for monitoring hitch angle γ in relation to jackknife angle.

$$\cos\overline{y}=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

where,

$$a=L^2\tan^2\delta(\max)+W^2;$$

$$b=2LD\tan^2\delta(\max);\text{ and}$$

$$c=D^2\tan^2\delta(\max)-W^2.$$

In certain instances of backing the trailer **12**, a jackknife enabling condition can arise based on current operating parameters of the vehicle **14** in combination with a corresponding hitch angle γ. This condition can be indicated when one or more specified vehicle operating thresholds are met while a particular hitch angle γ is present. For example, although the particular hitch angle γ is not currently at the jackknife angle for the vehicle **14** and attached trailer **12**, certain vehicle operating parameters can lead to a rapid (e.g., uncontrolled) transition of the hitch angle γ to the jackknife angle for a current commanded trailer curvature and/or can reduce an ability to steer the trailer **12** away from the jackknife angle. One reason for a jackknife enabling condition is that trailer curvature control mechanisms (e.g., those in accordance with the disclosed subject matter) generally calculate steering commands at an instantaneous point in time during backing of a trailer **12**. However, these calculations will typically not account for lag in the steering control system of the vehicle **14** (e.g., lag in a steering EPAS controller). Another reason for the jackknife enabling condition is that trailer curvature control mechanisms generally exhibit reduced steering sensitivity and/or effectiveness when the vehicle **14** is at relatively high speeds and/or when undergoing relatively high acceleration.

Jackknife determining information may be received by the controller **28**, according to one embodiment, to process and characterize a jackknife enabling condition of the vehicle-trailer combination at a particular point in time (e.g., at the point in time when the jackknife determining information was sampled). Examples of the jackknife determining information include, but are not limited to, information characterizing an estimated hitch angle γ, information characterizing a vehicle accelerator pedal transient state, information characterizing a speed of the vehicle **14**, information characterizing longitudinal acceleration of the vehicle **14**, information characterizing a brake torque being applied by a brake system of the vehicle **14**, information characterizing a powertrain torque being applied to driven wheels of the vehicle **14**, and information characterizing the magnitude and rate of driver requested trailer curvature. In this regard, jackknife determining information would be continually monitored, such as by an electronic control unit (ECU) that carries out trailer backup assist (TBA) functionality. After receiving the jackknife determining information, a routine may process the jackknife determining information for determining if the vehicle-trailer combination attained the jackknife enabling condition at the particular point in time. The objective of the operation for assessing the jackknife determining information is determining if a jackknife enabling condition has been attained at the point in time defined by the jackknife determining information. If it is determined that a jackknife enabling condition is present at the particular point in time, a routine may also determine an applicable countermeasure or countermeasures to implement. Accordingly, in some embodiments, an applicable countermeasure will be selected dependent upon a parameter identified as being a key influencer of the jackknife enabling condition. However, in other embodiments, an applicable countermeasure will be selected as being most able to readily alleviate the jackknife enabling condition. In still another embodiment, a predefined countermeasure or predefined set of countermeasures may be the applicable countermeasure(s).

As previously disclosed with reference to the illustrated embodiments, during operation of the trailer backup assist system **10**, a driver of the vehicle **14** may be limited in the manner in which steering inputs may be made with the steering wheel **68** of the vehicle **14** due to the power assist steering system **62** being directly coupled to the steering wheel **68**. Accordingly, the steering input device **18** of the trailer backup assist system **10** may be used for inputting a desired curvature **26** of the trailer **12**, thereby decoupling such commands from being made at the steering wheel **68** of the vehicle **14**. However, additional embodiments of the trailer backup assist system **10** may have the capability to selectively decouple the steering wheel **68** from movement of steerable wheels of the vehicle **14**, thereby allowing the steering wheel **68** to be used for commanding changes in the desired curvature **26** of a trailer **12** or otherwise selecting a desired backing path during such trailer backup assist.

Referring now to FIG. **7**, one embodiment of the steering input device **18** is illustrated disposed on a center console **108** of the vehicle **14** proximate a shifter **110**. In this embodiment, the steering input device **18** includes a rotatable knob **30** for providing the controller **28** with the desired backing path of the trailer **12**. More specifically, the angular position of the rotatable knob **30** may correlate with a desired curvature, such that rotation of the knob to a different angular position provides a different desired curvature with an incremental change based on the amount of rotation and, in some embodiments, a normalized rate, as described in greater detail herein.

The rotatable knob **30**, as illustrated in FIGS. **7**-**8**, may be biased (e.g., by a spring return) to a center or at-rest position P(AR) between opposing rotational ranges of motion R(R), R(L). In the illustrated embodiment, a first one of the opposing rotational ranges of motion R(R) is substantially equal to a second one of the opposing rotational ranges of motion R(L), R(R). To provide a tactile indication of an amount of rotation of the rotatable knob **30**, a force that biases the knob toward the at-rest position P(AR) can increase (e.g., non-linearly) as a function of the amount of rotation of the rotatable knob **30** with respect to the at-rest position P(AR). Additionally, the rotatable knob **30** can be configured with position indicating detents such that the driver can positively feel the at-rest position P(AR) and feel the ends of the opposing rotational ranges of motion R(L), R(R) approaching (e.g., soft end stops). The rotatable knob **30** may generate a desired curvature value as function of an amount of rotation of the rotatable knob **30** with respect to the at-rest position P(AR) and a direction of movement of the rotatable knob **30** with respect to the at-rest position P(AR). It is also contemplated that the rate of rotation of the rotatable knob **30** may also be used to determine the desired curvature output to the controller **28**. The at-rest position P(AR) of the knob corresponds to a signal indicating that the vehicle **14** should be steered such that the trailer **12** is backed along a substantially straight backing path (zero trailer curvature request from the driver), as defined by the longitudinal direction **22** of the trailer **12** when the knob was returned to the at-rest position P(AR). A maximum clockwise and anti-clockwise position of the knob (i.e., limits of the opposing rotational ranges of motion R(R), R(L)) may each correspond to a respective signal indicating a tightest radius of curvature (i.e., most acute trajectory or smallest radius of curvature) of a path of travel of the trailer **12** that is possible without the corresponding vehicle steering information causing a jackknife condition.

As shown in FIG. **8**, a driver can turn the rotatable knob **30** to provide a desired curvature **26** while the driver of the vehicle **14** backs the trailer **12**. In the illustrated embodiment, the rotatable knob **30** rotates about a central axis between a center or middle position **114** corresponding to a substantially straight backing path **26** of travel, as defined by the longitudinal direction **22** of the trailer **12**, and various rotated positions **116**, **118**, **120**, **122** on opposing sides of the middle position **114**, commanding a desired curvature **26** corresponding to a radius of the desired backing path of travel for the trailer **12** at the commanded rotated position. It is contemplated that the rotatable knob **30** may be configured in accordance with embodiments of the disclosed subject matter and omit a means for being biased to an at-rest position P(AR) between opposing rotational ranges of motion. Lack of such biasing may allow a current rotational position of the rotatable knob **30** to be maintained until the rotational control input device is manually moved to a different position. It is also conceivable that the steering input device **18** may include a non-rotational control device that may be configured to selectively provide a desired curvature **26** and to override or supplement an existing curvature value. Examples of such a non-rotational control input device include, but are not limited to, a plurality of depressible buttons (e.g., curve left, curve right, and travel straight), a touch screen on which a driver traces or otherwise inputs a curvature for path of travel commands, a button that is translatable along an axis for allowing a driver to input backing path commands, or a joystick type input and the like.

Referring to FIG. **9**, an example of using the steering input device **18** for dictating a curvature of a desired backing path of travel (POT) of the trailer **12** while backing up the trailer **12** with the vehicle **14** is shown. In preparation of backing the trailer **12**, the driver of the vehicle **14** may drive the vehicle **14** forward along a pull-thru path (PTP) to position the vehicle **14** and trailer **12** at a first backup position B**1**. In the first backup position B**1**, the vehicle **14** and trailer **12** are longitudinally aligned with each other such that a longitudinal centerline axis L**1** of the vehicle **14** is aligned with (e.g., parallel with or coincidental with) a longitudinal centerline axis L**2** of the trailer **12**. It is disclosed herein that such alignment of the longitudinal axis L**1**, L**2** at the onset of an instance of trailer backup functionality is not a requirement for operability of a trailer backup assist system **10**, but may be done for calibration.

After activating the trailer backup assist system **10** (e.g., before, after, or during the pull-thru sequence), the driver begins to back the trailer **12** by reversing the vehicle **14** from the first backup position B**1**. So long as the rotatable knob **30** of the trailer backup steering input device **18** remains in the at-rest position P(AR) and no other steering input devices **18** are activated, the trailer backup assist system **10** will steer the vehicle **14** as necessary for causing the trailer **12** to be backed along a substantially straight path of travel, as defined by the longitudinal direction **22** of the trailer **12**, specifically the centerline axis L**2** of the trailer **12**, at the time when backing of the trailer **12** began. When the trailer **12** reaches the second backup position B**2**, the driver rotates the rotatable knob **30** to command the trailer **12** to be steered to the right (i.e., a knob position R(R) clockwise rotation). Accordingly, the trailer backup assist system **10** will steer the vehicle **14** for causing the trailer **12** to be steered to the right as a function of an amount of rotation of the rotatable knob **30** with respect to the at-rest position P(AR), a rate movement of the knob, and/or a direction of movement of the knob with respect to the at-rest position P(AR). Similarly, the trailer **12** can be commanded to steer to the left by rotating the rotatable knob **30** to the left. When the trailer **12** reaches backup position B**3**, the driver allows the rotatable knob **30** to return to the at-rest position P(AR) thereby causing the trailer backup assist system **10** to steer the vehicle **14** as necessary for causing the trailer **12** to be backed along a substantially straight path of travel as defined by the longitudinal centerline axis L**2** of the trailer **12** at the time when the rotatable knob **30** was returned to the at-rest position P(AR). Thereafter, the trailer backup assist system **10** steers the vehicle **14** as necessary for causing the trailer **12** to be backed along this substantially straight path to the fourth backup position B**4**. In this regard, arcuate portions of a path of travel POT of the trailer **12** are dictated by rotation of the rotatable knob **30** and straight portions of the path of travel POT are dictated by an orientation of the centerline longitudinal axis L**2** of the trailer **12** when the knob is in/returned to the at-rest position P(AR).

In the embodiment illustrated in FIG. **9**, in order to activate the trailer backup assist system **10**, the driver interacts with the trailer backup assist system **10** and the automatically steers as the driver reverses the vehicle **14**. As discussed above, the driver may command the trailer backing path by using a steering input device **18** and the controller **28** may determine the vehicle steering angle to achieve the desired curvature **26**, whereby the driver controls the throttle and brake while the trailer backup assist system **10** controls the steering.

With reference to FIG. **10**, a method of operating one embodiment of the trailer backup assist system **10** is illustrated, shown as one embodiment of the operating routine **132** (FIG. **2**). At step **134**, the method is initiated by the trailer backup assist system **10** being activated. It is contemplated that this may be done in a variety of ways, such a making a selection on the display **82** of the vehicle HMI **80**. The next step **136**, then determines the kinematic relationship between the attached trailer **12** and the vehicle **14**. To determine the kinematic relationship, various parameters of the vehicle **14** and the trailer **12** must be sensed, input by the driver, or otherwise determined for the trailer backup assist system **10** to generate steering commands to the power assist steering system **62** in accordance with the desired curvature or backing path **26** of the trailer **12**. As disclosed with reference to FIGS. **3-6**, the kinematic parameters to define the kinematic relationship include a length of the trailer **12**, a wheel base of the vehicle **14**, a distance from a hitch connection to a rear axle of the vehicle **14**, and a hitch angle γ between the vehicle **14** and the trailer **12**, among other variables and parameters as previously described. Accordingly, after the kinematic relationship is determined, the trailer backup assist system **10** may proceed at step **160** to determine the current hitch angle by processing the hitch angle estimation routine **130**.

As shown in FIG. **11**, one embodiment of a kinematic relationship between the trailer **12** an the vehicle **14** is developed with the illustrated schematic diagram that shows the geometry of a vehicle and a trailer overlaid with a two-dimensional x-y coordinate system, identifying variables, such as the trailer yaw rate ω_2 and the vehicle yaw rate ω_1, which are used to determine the corresponding hitch angle γ. As such, hitch angle estimation may be determined using trailer yaw rate signal ω_2, vehicle speed signal v_1 and vehicle yaw rate signal ω_1. More specifically, the yaw rate of the trailer is given by the following kinematic equation:

$$\omega_2 = \frac{v_1}{D}\sin\gamma - \frac{L}{D}\cos\gamma\omega_1$$

This kinematic equation can be rearranged to estimate trailer hitch angle γ, as follows:

$$\gamma = \sin^{-1}\frac{v_1\omega_2 D + \omega_1 L\sqrt{v_1^2 + \omega_1^2 L^2 - \omega_2^2 D^2}}{v_1^2 + \omega_1^2 L^2} \quad \text{or}$$

$$\gamma = \sin^{-1}\frac{\omega_2 D}{\sqrt{v_1^2 + \omega_1^2 L^2}} + \tan^{-1}\frac{\omega_1 L}{v_1}$$

Referring to FIG. **12**, one embodiment of the hitch angle estimation routine **130** is illustrated, whereby the above-noted kinematic relationship is utilized to instantaneously estimate the hitch angle γ. At step **138**, the sensor signals are received for executing the steps to determine the hitch angle γ. The sensor signals may include the trailer yaw rate signal ω_2, the vehicle speed signal v_1, and the vehicle yaw rate signal ω_1, along with other sensor signals that may be used in some embodiments, such as the steering angle δ signal, trailer lateral acceleration a_{y2}, the measure hitch angle from the hitch angle sensor **44** among other potential sensor signals. At step **140**, these signals may be filtered and any potential offsets may be compensated before proceeding to further process the sensor signals.

Still referring to FIG. **12**, in one embodiment, the vehicle speed v_1 may be received from the speed sensor **58** on the vehicle **14** and not require any further processing or derivation to proceed with calculating the instantaneous hitch angle γ. However, at step **142**, in some embodiments, the vehicle speed v_1 may be derived from wheel speed sensors on the vehicle **14**, the positioning device **56**, or other conceivable means to determine the vehicle speed v_1. Also, according to one embodiment, the vehicle yaw rate ω_1 may be received directly from the yaw rate sensor **60** on the vehicle **14** and not necessitate any further derivation. However, it is also contemplated that at step **142**, the vehicle yaw rate ω_1 may additionally or alternatively be derived from left and right wheel speed sensors on the vehicle **14**. Further, according to an additional embodiment, the vehicle yaw rate ω_1 may be derived from the steering angle δ of the vehicle **14** and the vehicle speed v_1, along with the vehicle wheelbase W, which is known or otherwise stored in the memory **86** of the controller **28**. One embodiment of an equation to determine the vehicle yaw rate ω_1 based on the steering angle δ and the vehicle speed v_1 is as follows:

$$\omega_1 = -\frac{v_1}{W}\tan\delta.$$

As shown in FIG. **12**, the trailer yaw rate ω_2 may also be provided directly by the sensor system **16** at step **138** or determined from processing the sensor signals at step **142**. For instance, the trailer yaw rate ω_2 may be received directly from the yaw rate sensor **25** mounted on the trailer **12**. Additionally or alternatively, the trailer yaw rate ω_2 may be derived from the left and right wheel speed sensors **23** on the trailer **12**. Also, in addition or in the alternative, the trailer yaw rate ω_2 may be calculated using the trailer speed v_2 and the lateral acceleration a_{y2} of the trailer, as sensed by the accelerometer **27** of the trailer sensor module **20**, in one embodiment. One embodiment of such an equation to determine the trailer yaw rate ω_2 is as follows, where lateral acceleration a_{y2} of the trailer may be derived from the accelerometer **27** and trailer speed v_2 may be derived from the wheel speed sensor **23**:

$$\omega_2 = \frac{a_{y2}}{v_2}.$$

When wheel speed sensors **23** are not available or otherwise included on the trailer sensor module **20** or the sensor system **16**, the above-referenced kinematic equation may then be reordered to solve for the trailer speed v_2, as follows:

$$v_1^2 + \omega_1^2 L^2 - D^2\omega_2^2 = (v_1\cos\gamma + L\sin\gamma\omega_1)^2 = v_2^2,\ v_2 = \sqrt{v_1^2 + \omega_1^2 L^2 - D^2\omega_2^2}\ .$$

As such, the accuracy of the trailer speed v_2 and the resultant calculated hitch angle γ will rely more heavily on the accuracy of the other sensors utilized to determine the vehicle speed v_1, vehicle yaw rate ω_1, and the trailer yaw rate ω_2, as previously mentioned, along with the accuracy of the vehicle and trailer dimensions L and D.

As illustrated in FIG. **12**, when the sensor signals have been received and the necessary parameters received or otherwise determined, at step **144**, the controller **28** processes the following equation, based on the kinematic relationship of the trailer **12** and the vehicle **14**, to solve for the instantaneous hitch angle γ.

$$\gamma = \sin^{-1}\left(\frac{v_1\omega_2 D + \omega_1 L\sqrt{v_1^2 + \omega_1^2 L^2 - \omega_2^2 D^2}}{v_1^2 + \omega_1^2 L^2}\right)$$

Further, should the sensor system **16** be unequipped to provide the controller **28** with the trailer yaw rate ω_2, in another embodiment, at step **144**, the instantaneous hitch angle γ may still be determined, as follows:

$$\gamma = \sin^{-1}\frac{v_2\omega_1 L \pm v_1\sqrt{v_1^2 + \omega_1^2 L^2 - v_2^2}}{v_1^2 + \omega_1^2 L^2}$$

or

$$\gamma = \sin^{-1}\frac{v_2}{\sqrt{v_1^2 + \omega_1^2 L^2}} - \tan^{-1}\frac{v_1}{\omega_1 L}.$$

In this equation, the hitch angle γ is determined based on the vehicle speed v_1, trailer speed v_2, and vehicle yaw rate ω_1, whereby such parameters are relied upon more heavily for accuracy. The above equation solving for the hitch angle γ is based on a kinematic relationship for the trailer speed v_2, which does not incorporate the trailer yaw rate ω_2, as follows:

$$v_2 = v_1 \cos\gamma + L\sin\gamma\omega_1.$$

With this identified relationship, it is conceivable that if the hitch angle is known by another means, such the hitch angle sensor **44**, the trailer speed v_2 may also be solved for with the above equation.

Also, trailer speed v_2 may be determined with the following equation, based on the trail yaw rate ω_2 and the lateral acceleration a_{y2} of the trailer, such as from the trailer yaw rate sensor **25** and the accelerometer **27**, respectively.

$$v_2 = \frac{a_{y2}}{\omega_2}$$

Accordingly, when the trailer speed v_2 is sensed or otherwise determined from other variables, such as the trail yaw rate ω_2 and the lateral acceleration a_{y2} of the trailer, then the hitch angle γ calculation may incorporate this parameter, as follows:

$$\gamma = \sin^{-1}\frac{v_1\omega_2 D + v_2\omega_1 L}{v_1^2 + \omega_1^2 L^2}.$$

Referring again to FIG. **12**, at step **146** the presently estimated hitch angle γ may be filtered to provide a more accurate estimate. More specifically, the hitch angle γ estimated with the hitch angle estimation routine **130** may be less accurate at low vehicle speed v_1 when the denominator of the above-noted equations approaches zero. In one embodiment, the hitch angle γ may be filtered by using the trailer yaw rate ω_2 and the vehicle yaw rate ω_1. For instance, the estimated hitch angle γ could be filtered with a discrete-time Kalman filter, whereby the filtered hitch angle estimate is obtained from the following equation:

$$\hat{\gamma}_{k+1} = \hat{\gamma}_k + (\omega_{2,k} - \omega_{1,k})\cdot T_s + K_k\cdot(\gamma_k - \hat{\gamma}_k).$$

In this embodiment, T_s is the sampling time, k is an integer representing the k^{th} sampling instance, K_k is the Kalman gain, and γ_k is the calculated hitch angle from the above-noted equations.

However, when the vehicle **14** is stopped, the filtered estimate is “frozen” at the previously known good value, i.e.:

$$\hat{\gamma}_{k+1} = \hat{\gamma}_k.$$

This is the filter to determine when the vehicle **14** is stopped or traveling at low speeds, as provided at step **148**, which precedes step **144**. If the vehicle **14** is not determined to be stopped or traveling slow at step **148**, the hitch angle γ is estimated and filtered at steps **144** and **146**, as described above. When the result of an accurate hitch angle γ from the above-noted kinematic equations is temporarily not available or inaccurate (e.g., at low speed), the filtered estimate is obtained from the following equation:

$$\hat{\gamma}_{k+1} = \hat{\gamma}_k + (\omega_{2,k} - \omega_{1,k})\cdot T_s.$$

In an additional or alternative embodiment, the hitch angle γ may be filtered by using the vehicle yaw rate ω_1 and vehicle speed v_1. For instance, this may be desired if the trailer yaw rate ω_2 is noisy, whereby the filtering described above and shown in FIG. **12** may not generate desired results. In this case, the since the diagram illustrated in FIG. **11** is nonlinear, a nonlinear extension of the Kalman filter, which is often referred to as extended Kalman filter by those skilled in the art, may be applied. To do so, when the results are generally available and accurate for the hitch angle γ determined at step

144, such as when the vehicle 14 is moving a sufficient speed, the filter hitch angle may be estimated from the following equation:

$$\hat{\gamma}_{k+1} = \hat{\gamma}_k + \left(\frac{v_{1,k}}{D}\sin\hat{\gamma}_k - \frac{\omega_{1,k}\cdot L}{D}\cos\hat{\gamma}_k - \omega_{1,k}\right)\cdot T_s + K_k\cdot(\gamma_k - \hat{\gamma}_k)$$

Accordingly, when the results are temporarily not available or inaccurate for the hitch angle γ determined at step 144, such as at low speeds, the filtered hitch angle estimate may is obtained from the following equation:

$$\hat{\gamma}_{k+1} = \hat{\gamma}_k + \left(\frac{v_{1,k}}{D}\sin\hat{\gamma}_k - \frac{\omega_{1,k}\cdot L}{D}\cos\hat{\gamma}_k - \omega_{1,k}\right)\cdot T_s$$

There are many alternative ways to express the Kalman gain, and one of the formulations is given as follows:

$$A_k = \left(\frac{v_{1,k}}{D}\cos\hat{\gamma}_k + \frac{\omega_{1,k}\cdot L}{D}\sin\hat{\gamma}_k\right)\cdot T_s + 1,$$

$$K_k = P_k(P_k + R)^{-1},$$

$$P_{k+1} = A_k(1 - K_k)P_k A_k^T + Q,$$

where A_k is the derivative matrix, Q is the process noise covariance, R is the measurement noise covariance, and P_k is the estimation error covariance.

As shown in FIG. 12, upon estimating and filtering the hitch angle γ, at step 152 the trailer length D and vehicle wheelbase W can be estimated or refined to improve the accuracy of later calculations. As such, trailer length D may be estimated based on the trailer speed v_2, the vehicle speed v_1, the vehicle yaw rate ω_1, and the trailer yaw rate ω_2, as determined from the previous steps of the hitch angle estimation routine 130. For instance, if the drawbar length L between hitch point and rear axle of the vehicle 14 is measured or otherwise known, the trailer length D can be calculated as follows:

$$D = \sqrt{\frac{v_1^2 + \omega_1^2 L^2 - v_2^2}{\omega_2^2}}.$$

Similarly, if the trailer length D is measured or otherwise known, the drawbar length L between hitch point and rear axle of the vehicle 14 may be estimated based on the trailer speed v_2, the vehicle speed v_1, the vehicle yaw rate ω_1, and the trailer yaw rate ω_2, as determined from the previous steps of the hitch angle estimation routine 130. As such, the drawbar length L can be calculated as follows:

$$L = \sqrt{\frac{v_2^2 + \omega_2^2 D^2 - v_1^2}{\omega_1^2}}.$$

As also shown in FIG. 12, at step 154 the hitch angle estimation routine 130 may proceed to estimate or refine the trailer turning radius r_2 and the curvature κ_2 of the trailer trajectory for improving the accuracy of later calculations. This may be done using the following equations:

$$r_2 = \frac{v_2}{\omega_2},$$

and

$$\kappa_2 = \frac{\omega_2}{v_2}.$$

Referring again to FIG. 10, at step 160 the hitch angle γ is determined between the vehicle 14 and the trailer 12, although this may be done continuously during operation of the trailer backup assist system 10. It is contemplated that in additional embodiments of the trailer backup assist system 10 that the steps of determining the kinematic relationship and sensing the hitch angle γ may occur before the trailer backup assist system 10 is activated or at any other time before steering commands are generated. Accordingly, at step 162, the position and rate of changes is received from the steering input device 18, such as the angular position and rate of rotation of the rotatable knob 30, for determining the desired curvature 26. At step 164, steering commands may be generate based on the desired curvature, correlating with the position and rate of change of the steering input device 18. The steering commands and actuation commands generated may be generated in conjunction with processing of the curvature routine 98, as previous discussed. At step 166, the steering commands and actuation commands have been executed to guide the trailer 12 on the desired curvature provided by the steering input device 18.

In parallel with performing the operations for receiving the trailer backup assist requests, determining the desired curvature 26 of the trailer 12, and generating the vehicle steering commands, the trailer backup assist system 10 may perform an operation for monitoring if an unacceptable trailer backup condition exists. Examples of such monitoring include, but are not limited to assessing a hitch angle γ to determine if a hitch angle γ threshold is exceeded, assessing a backup speed to determine if a backup speed threshold is exceeded, assessing vehicle steering angle to determine if a vehicle steering angle threshold is exceeded, assessing other operating parameters (e.g., vehicle longitudinal acceleration, throttle pedal demand rate and hitch angle rate) for determining if a respective threshold value is exceeded, and the like. Backup speed can be determined from the wheel speed information obtained from one or more speed sensors 58 of the vehicle 14. If it is determined that an unacceptable trailer backup condition exists, an operation may be performed for causing the current path of travel of the trailer 12 to be inhibited (e.g., stopping motion of the vehicle 14), followed by the operation being performed for ending the current trailer backup assist instance. It is disclosed herein that prior to and/or in conjunction with causing the current trailer path to be inhibited, one or more actions (e.g., operations) can be implemented for providing the driver with feedback (e.g., a warning) that such an unacceptable hitch angle condition is impending or approaching. In one example, if such feedback results in the unacceptable hitch angle condition being remedied prior to achieving a critical condition, the method can continue with providing trailer backup assist functionality in accordance with operations. Otherwise, the method can proceed to operation for ending the current trailer backup assist instance. In conjunction with performing the operation for ending the current trailer backup assist instance, an operation can be performed for controlling movement of the vehicle 14 to correct or limit a jackknife condition (e.g., steering the vehicle **14**, decelerating the vehicle **14**, limiting magnitude and/or rate of driver requested trailer curvature input, limiting magnitude and/or rate of the steering command, and/or the like to preclude the hitch angle from being exceeded).

With the sensor system **16** and/or controller **28** providing the trailer yaw rate ω_2, this parameter may additionally or alternatively be utilized to improve the electronic stability control provided with the power assist steering system **62** when the vehicle **14** is towing a trailer. Some electronic stability control systems use a so called bicycle model (without trailer) to obtain a reference vehicle yaw rate commanded by the driver. However, when the vehicle is towing a trailer, the towing vehicle may exhibit more oversteer or more understeer tendencies during a turn, compared to the same vehicle without a trailer attached. Thus the electronic stability control performance may degrade, and/or unintended activations may occur, when the vehicle is towing a trailer.

By using the sensed or otherwise determined trailer yaw rate signal ω_2, together with other electronic stability control signals, the additional oversteer or understeer tendencies of the vehicle (compared to when not towing a trailer) can be identified. Accordingly, the existing electronic stability control system can be sensitized or desensitized (e.g., by modifying the control thresholds for the brake and engine controllers). The brake and engine control actions can also be increased or reduced by changing the controller gains. Therefore, an additional controller which uses trailer yaw rate signal ω_2 (or the difference between trailer and vehicle yaw rate, i.e., $\omega_2-\omega_1$) and its derivative may be integrated with the existing electronic stability control system. Such a controller is beneficial for improving the overall vehicle-trailer combination stability

In addition, it is contemplated that using the trailer yaw rate signal ω_2 and trailer lateral acceleration signal a_{y2}, together with other standard electronic stability control signals, may further identify additional oversteer or understeer tendencies of the vehicle. It is also conceivable that a controller that uses the trailer hitch angle γ as a feedback signal may be integrated with the existing electronic stability control system for improving the overall vehicle-trailer combination stability.

As previously mentioned, the hitch angle γ determined by the hitch angle estimation routine **130** may also be used to identify and stabilize a swaying trailer. More specifically, the vehicle-trailer combination becomes less damped when its speed is increased. With any driver inputs or external disturbances, the trailer may start to oscillate and the oscillation may sustain for a long time. If the speed is above certain "critical speed", the system may become unstable, causing the oscillation amplitude to grow larger and eventually cause vehicle instability and/or a jackknife condition. A controller which uses trailer yaw rate signal ω_2 (or the difference between trailer and vehicle yaw rate, i.e., $\omega_2-\omega_1$) and its derivative can be designed to actively control the vehicle/trailer to damping out the oscillation. In addition, the trailer yaw rate ω_2 and the trailer lateral acceleration a_{y2}, together with other standard electronic stability control signals, may be used to stabilize a swaying trailer. Since both trailer yaw rate signal ω_2 and trailer lateral acceleration signal a_{y2} directly provide information about the trailer motion, they can be used to quickly identify whether the trailer is swaying.

It will be understood by one having ordinary skill in the art that construction of the described invention and other components is not limited to any specific material. Other exemplary embodiments of the invention disclosed herein may be formed from a wide variety of materials, unless described otherwise herein.

For purposes of this disclosure, the term "coupled" (in all of its forms, couple, coupling, coupled, etc.) generally means the joining of two components (electrical or mechanical) directly or indirectly to one another. Such joining may be stationary in nature or movable in nature. Such joining may be achieved with the two components (electrical or mechanical) and any additional intermediate members being integrally formed as a single unitary body with one another or with the two components. Such joining may be permanent in nature or may be removable or releasable in nature unless otherwise stated.

It is also important to note that the construction and arrangement of the elements of the invention as shown in the exemplary embodiments is illustrative only. Although only a few embodiments of the present innovations have been described in detail in this disclosure, those skilled in the art who review this disclosure will readily appreciate that many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.) without materially departing from the novel teachings and advantages of the subject matter recited. For example, elements shown as integrally formed may be constructed of multiple parts or elements shown as multiple parts may be integrally formed, the operation of the interfaces may be reversed or otherwise varied, the length or width of the structures and/or members or connector or other elements of the system may be varied, the nature or number of adjustment positions provided between the elements may be varied. It should be noted that the elements and/or assemblies of the system may be constructed from any of a wide variety of materials that provide sufficient strength or durability, in any of a wide variety of colors, textures, and combinations. Accordingly, all such modifications are intended to be included within the scope of the present innovations. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the desired and other exemplary embodiments without departing from the spirit of the present innovations.

It will be understood that any described processes or steps within described processes may be combined with other disclosed processes or steps to form structures within the scope of the present invention. The exemplary structures and processes disclosed herein are for illustrative purposes and are not to be construed as limiting.

It is also to be understood that variations and modifications can be made on the aforementioned structures and methods without departing from the concepts of the present invention, and further it is to be understood that such concepts are intended to be covered by the following claims unless these claims by their language expressly state otherwise.

What is claimed is:

1. A trailer backup assist system comprising:

a trailer sensor module generating at least one of a trailer yaw rate or a trailer speed;

a vehicle sensor system generating a vehicle yaw rate and a vehicle speed; and

a controller estimating a hitch angle based on the vehicle yaw rate, vehicle speed, and one of the trailer yaw rate or the trailer speed in view of a kinematic relationship.

2. The trailer backup assist system of claim **1**, wherein the kinematic relationship between the trailer and the vehicle includes a known length of the trailer, a known drawbar length of the vehicle, and a known wheelbase of the vehicle, such that the hitch angle is instantaneously estimated with the controller.

3. The trailer backup assist system of claim 1, wherein the trailer sensor module includes a yaw rate sensor attached to the trailer that generates the trailer yaw rate.

4. The trailer backup assist system of claim 1, wherein the trailer sensor module includes a sensor that generates a lateral acceleration of the trailer, and wherein the trailer yaw rate is derived based on the lateral acceleration and a trailer speed.

5. The trailer backup assist system of claim 1, wherein the trailer sensor module includes left and right wheel speed sensors on laterally opposing wheels of the trailer.

6. The trailer backup assist system of claim 1, wherein the vehicle sensor system includes a yaw rate sensor that generates the vehicle yaw rate.

7. The trailer backup assist system of claim 1, wherein the vehicle sensor system includes a wheel speed sensor that generates the vehicle speed and a steering angle sensor that generates a steering angle of the vehicle, whereby the vehicle yaw rate is determined based on the steering angle, the vehicle speed, and a wheelbase of the vehicle.

8. The trailer backup assist system of claim 1, wherein the vehicle sensor system includes left and right wheel speed sensors on laterally opposing wheels of the vehicle for determining the vehicle speed and the vehicle yaw rate.

9. A system for estimating a hitch angle between a vehicle and a trailer, comprising:

a first sensor coupled with the trailer for determining a trailer yaw rate;

a second sensor coupled with the vehicle for determining a vehicle yaw rate; and

a controller estimating a hitch angle based on the trailer yaw rate, the vehicle yaw rate, and a vehicle speed in view of a kinematic relationship between the trailer and the vehicle.

10. The system of claim 9, wherein the kinematic relationship includes a length of the trailer and a drawbar length of the vehicle, and wherein the hitch angle estimated by the controller is filtered by combining a hitch angle value based on the kinematic relationship with a hitch angle rate determined by a difference between the trailer yaw rate and the vehicle yaw rate.

11. The system of claim 9, wherein the first sensor includes a yaw rate sensor that generates the trailer yaw rate.

12. The system of claim 9, wherein the first sensor includes left and right wheel speed sensors on laterally opposing wheels of the trailer, and wherein speed signals from the left and right wheel speed sensors are processed to derive the trailer yaw rate.

13. The system of claim 9, further comprising:

a third sensor coupled with the trailer that generates a lateral acceleration of the trailer, wherein the first sensor generates a speed of the trailer, such that the trailer yaw rate is derived based on the lateral acceleration and the speed of the trailer.

14. The system of claim 9, wherein the second sensor includes a wheel speed sensor that generates the vehicle speed and a steering angle sensor that generates a steering angle of the vehicle, and wherein the vehicle yaw rate is determined based on the vehicle speed and the steering angle.

15. The system of claim 9, further comprising:

a steering input device for inputting a desired curvature of the trailer when reversing the vehicle, wherein the controller generates a steering command for the vehicle to guide the trailer on the desired curvature based on the estimated hitch angle.

16. A method for estimating a hitch angle between a vehicle and a trailer, comprising:

sensing a first yaw rate of the trailer;

sensing a second yaw rate of the vehicle;

sensing a speed of the vehicle;

determining an instantaneous hitch angle based on the first and second yaw rates and the speed of the vehicle in view of a kinematic relationship between the trailer and the vehicle; and

generating a steering command for the vehicle based on the instantaneous hitch angle to guide the trailer on a desired backing path, wherein the desired backing path is determined by an input received from a steering input device of a trailer backup assist system.

17. The method of claim 16, wherein the first yaw rate of the trailer is sensed based on a sensed lateral acceleration of the trailer, and wherein the instantaneous hitch angle is filtered by combining a hitch angle value based on the kinematic relationship with a hitch angle rate determined by a difference between the first and second yaw rates of the trailer and the vehicle.

18. The method of claim 16, wherein the first yaw rate of the trailer is sensed with left and right wheel speed sensors on laterally opposing wheels of the trailer, and wherein speed signals from the left and right wheel speed sensors are processed to derive the first yaw rate of the trailer.

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